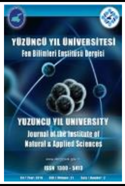
Yüzüncü Yıl University Journal of the Institute of Natural & Applied Sciences Volume 27, Issue 1 (April), 64-72, 2022

Yüzüncü Yıl University
Journal of the Institute of Natural & Applied Sciences

https://dergipark.org.tr/tr/pub/yyufbed



Research Article

Estimation of Memristor Hysteresis Curve with Fuzzy Logic Designer

İshak PARLAR[*1], M. Nuri ALMALI[1], Ali Can ÇABUKER[1]

[1]Van Yüzüncü Yıl University, Faculty of Engineering, Department of Electrical and Electronics Engineering 65080, Van, Turkey

İshak PARLAR, ORCID No:0000-0002-3383-8091, M. Nuri ALMALI, ORCID No:0000-0003-2763-4452, Ali Can ÇABUKER, ORCID No:0000-0003-2011-2117

*Corresponding author e-mail ishakparlar@yyu.edu.tr

Article Info

Received: 08.02.2022
Accepted: 16.03.2022
Online April 2022
DOI:10.53433/yyufbed.1070358

Keywords
Linear dopant drift TiO_2 model,
Hysteresis loop,
Fuzzy logic designer,
Analog circuit applications,
Current-voltage (I-V) curve

Abstract: In this study aimed to optimize the predictable region of the memristor hysteresis curve with the fuzzy logic designer tool by using the linear, doped drift TiO_2 model as a memristor emulation circuit. Using this model, the current-voltage (I-V) curve of the memristor characteristic, that is, the hysteresis loop was created. In analog application studies, especially in filter circuits, being able to obtain a hysteresis loop in a certain frequency range leads to significant changes in the quality of the filter. At this point, various trial and error tests were performed for the most suitable parameter points. Here, the optimum hysteresis loop parameters were determined using a fuzzy logic designer. As a result, more practical and more stable results were obtained about the optimum hysteresis loop depending on the current-voltage and frequency information. In this way, users can get more predictable responses by determining the parameters according to the desired purpose and need. Especially in analog and digital electronic applications, they can approach the result more decisively by determining both the time loss and the workable area easily.

Bulanık Mantık Tasarımcısı ile Memristor Histerezis Eğrisinin Tahmini

Makale Bilgileri

Geliş: 08.02.2022
Kabul: 16.03.2022
Online Nisan 2022
DOI:10.53433/yyufbed.1070358

Anahtar Kelimeler
Lineer dopant drift TiO_2 modeli,
Histerezis döngüsü,
Bulanık mantık tasarımcısı,
Analog devre uygulamaları,
Akım-gerilim (I-V) eğrisi

Öz: Bu çalışmada memristör taklit devresi olarak doğrusal, katkılı sürüklenme TiO_2 modeli kullanılarak bulanık mantık tasarımcısı aracı ile memristör histerezis eğrisinin tahmin edilebilir bölgesinin optimize edilmesi amaçlanmıştır. Bu model kullanılarak memristör karakteristiğinin akım-gerilim (I-V) eğrisi yani histerezis döngüsü oluşturulmuştur. Analog uygulama çalışmalarında özellikle filtre devrelerinde belirli bir frekans aralığında histerezis döngüsünü elde edebilmek filtrenin kalitesinde önemli değişikliklere yol açmaktadır. Bu noktada en uygun parametre noktaları için çeşitli deneme yanılma testleri yapıldı. Burada, optimum histerezis döngü parametreleri, bulanık mantık tasarımcısı kullanılarak belirlendi. Sonuç olarak akım-voltaj ve frekans bilgisine bağlı olarak optimum histerezis döngüsü hakkında daha pratik ve daha kararlı sonuçlar elde edildi. Bu sayede kullanıcılar istenilen amaca ve ihtiyaca göre parametreleri belirleyerek daha öngörülebilir tepkiler alabilmektedir. Özellikle analog ve digital elektronik uygulama çalışmalarında hem zaman kaybını hem de çalışılabilir bölgeyi rahat belirleyerek sonuca daha kararlı yaklaşabilmektedirler.

1. Introduction

The memristor, which emerged as a missing circuit element, is used in many areas from neural networks to op-amp applications (Lin et al., 2020; Parlar et al., 2021). When the current-voltage characteristic of the memristor is plotted on the coordinate axis, a hysteresis curve is obtained. The hysteresis curves of the simulated circuits in the literature are different (Yener et al., 2014; Muthuswamy, 2010; Biolek et al., 2010). Memristors with simulated circuits can be simulated with the help of a window function. From this point of view, a memristor model can be created with a window function created with fuzzy logic. The advantage of the created fuzzy logic-based window function is the flexibility in its modelling (Abdel-Kader & Abuelenin, 2015). The membership function in the fuzzy logic method is used in memristor applications. An example of this is neuro-fuzzy systems that emerge from the combination of neural networks and fuzzy logic (Marlen & Dorzhigulov, 2018). Fuzzy logic controller designs are useful in many simulative applications. An example of these is the arrangement of learning coefficients of memristor-based multilayer neural networks. Thus, positive success was achieved in the learning coefficient of 2%-3% compared to the fixed coefficients (Wen et al., 2018). Memristor applications have found a place not only in artificial neural networks, but also in the field of chaotic communication, which is a branch of communication. In the study, a memristor-based Lorenz chaotic circuit was used and the synchronization of two chaotic circuits was realized (Wen et al., 2013). The memristor hysteresis curve has been tried to be optimized in the studies. Also in the studies in the later stages of the optimization work, it is aimed to produce neuromorphic memristor hardware (Yakopcic et al., 2019). Materials with different component structures have been used experimentally for the physical neuromorphic applications of the memristor, which is a missing circuit element (Wlaźlak et al., 2019; Wang et al., 2017).

A fuzzy logic method designer was used to create the most suitable hysteresis curve by the users. In this study, apart from indirect parameters such as hysteresis curve D (physical thickness of the memristor-nm), uv (transition velocity of oxygen atoms, f/s) and p (positive coefficient), basic parameters such as current, voltage and frequency were optimized by a fuzzy logic method. By determining the limit ranges of these parameter values, a rule table was created by using the Gaussian curve in the fuzzy-logic designer.

The parameters of the system are introduced and the interface of the Fuzzy-Logic designer is given in chapter 2. In the last part, the most suitable hysteresis curve was found by interpreting the parameter values.

2. Material and Methods

First, the hysteresis curve of the memristor was constructed. The parameters of the hysteresis curve were determined. These determined parameters were optimized using the fuzzy logic designer toolbox in the MATLAB package program. In the Matlab package program, fuzzy logic rules and membership functions have been determined, which will include rules suitable for the memristor.

2.1. Hysteresis curve of memristor

Because of this feature of the memristor operating at low frequencies, the loop disappears at high frequencies in the hysteresis curve. When it draws high current from the source, (Figure 1) shows the relationship between current, voltage and frequency.

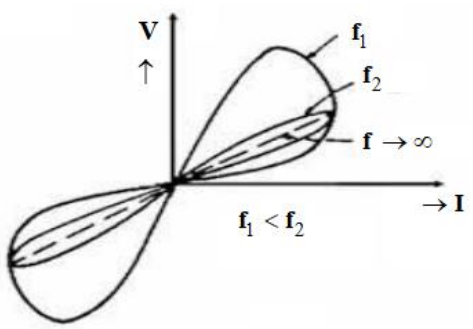


Figure 1. Hysterisis curve of memristor (Wen et al., 2018).

Using an example memristor window function, the parameters of the hysteresis curve are tested (Figure 2). One of the most common window functions, Joglekar (Chua & Kang, 1976) model was used.

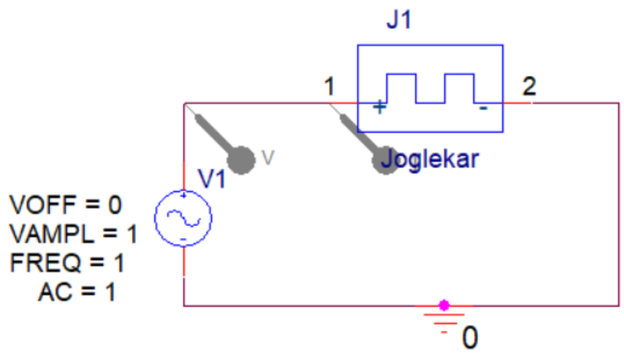


Figure 2. Schematic of linear drift fast TiO_2 memristor emulator circuit.

The memristor contains the derivative of magnetic flux with electric charge as its working principle.

```
.SUBCKT memristor Plus Minus PARAMS:
+ Ron=100 Roff=16K Rinit=11K D=10N uv=10F p=10
**********************************************
* DIFFERENTIAL EQUATION MODELING *
**********************************************
Gx 0 x value={ I(Emem)*uv*Ron/D^2*f(V(x),p)}
Cx x 0 1 IC={(Roff-Rinit)/(Roff-Ron)}
Raux x 0 1T
* RESISTIVE PORT OF THE MEMRISTOR *
******************************
Emem plus aux value={-I(Emem)*V(x)*(Roff-Ron)}
Roff aux minus {Roff}
**********************************************
*Flux computation*
**********************************************
Eflux flux 0 value={SDT(V(plus,minus))}
**********************************************
*Charge computation*
**********************************************
Echarge charge 0 value={SDT(I(Emem))}
**********************************************
* WINDOW FUNCTIONS
* FOR NONLINEAR DRIFT MODELING *
**********************************************
*window function, according to Joglekar
.func f(x,p)={1-(2*x-1)^(2*p)}
.ENDS memristor
```

The Pspice code given above defines the Joglekar window function memristor model (Figure 2). The beginning of this code part expresses the physical properties of the memristor, the middle part expresses the differential, flux, current and voltage equations, and the last part expresses the window function.

When a voltage or current is applied to the device, the dividing line between the TiO_2 and TiO_{2-x} layers constantly shifts as a function of the applied voltage or current. As a result, the resistance between the two electrodes is thereby changed. The thickness of the trapped area (D-w) and the doped area (the oxygen-deficient area) in the TiO_2 memristor are indicated by w (1).

$$M(q(t)) = \frac{\frac{d\varphi}{dt}}{\frac{dq}{dt}} = \frac{V(t)}{I(t)}$$

$$= R_{OFF}\left\{\left[1 + \frac{w_0}{D}\left(\frac{R_{ON}}{R_{OFF}} - 1\right)\right] - \frac{u_v R_{ON}}{D^2}\left(1 - \frac{R_{ON}}{R_{OFF}}\right)q(t)\right\} \quad (1)$$

$$\approx R_{OFF}\left\{1 - \frac{u_v R_{ON}}{D^2}q(t)\right\}$$

The graph formed due to the current-voltage characteristic of the memristor is not a straight line. Therefore, the relationship between the current passing through the memristor and the resulting voltage is hysterical (Kim et al., 2012).

2.2. Fuzzy logic designer

Mamdani logic controller, which is one of the most used inference methods in the fuzzy logic designer's MATLAB toolbox, can be used to form the learning basis of memristor-based multilayer neural networks (Joglekar & Wolf, 2009). In this study, a three-input and single-output system were designed with the fuzzy logic method. Each input was determined as low-medium and high with a triangular membership function. The breakpoints were determined by the Joglekar window function given in Figure 2. The structure of the general system is shown in (Figure 3).

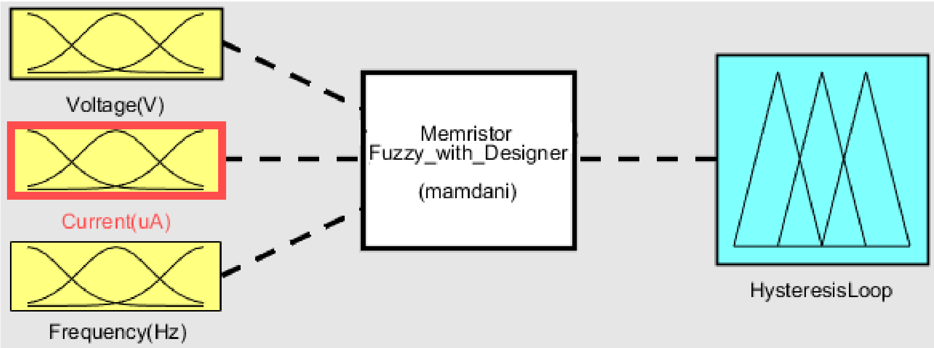


Figure 3. Fuzzy logic-based memristor hysteresis assessment model.

In the fuzzy logic design, a rule table was created by using the "trimf" function for each input (Figure 4). Here, it is possible to get different results by using many types of functions. An optimization method can also be used to make the best output estimation using the most ideal function. While forming the border points of the triangles, it becomes important at this point how many parts the total set will be divided into. It is possible to increase the parts called low, medium and high, as well as reduce them further. To get the best results, the fact that the triangles that are divided into parts are in intersection with other triangular regions affects the result positively.

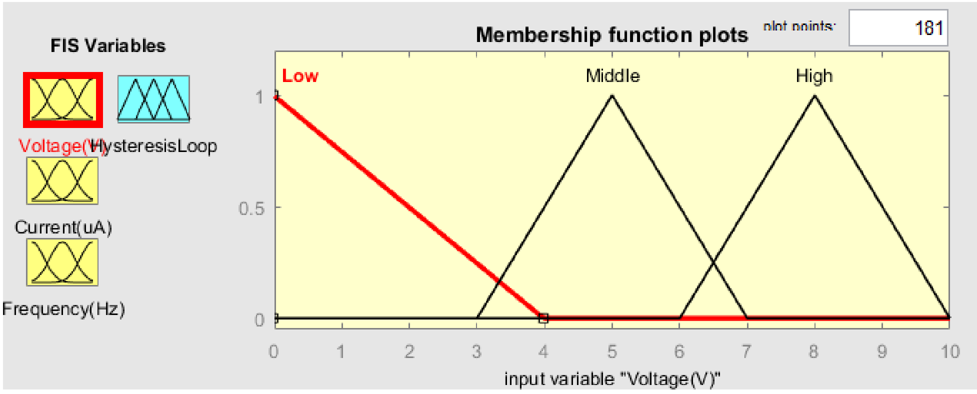


Figure 4. Representation of rule base functions for input parameters.

Possible membership functions are shown (Figure 5). After each function is selected, it should be done by taking advantage of the unique features of these functions while separating the membership parts. When we look at the literature, it is seen that the most common and good results are obtained with functions such as "trimf, gaussmf and gauss2mf". In this study, the "trimf" function was chosen to easily arrange and separate the intersection areas of the triangular regions.

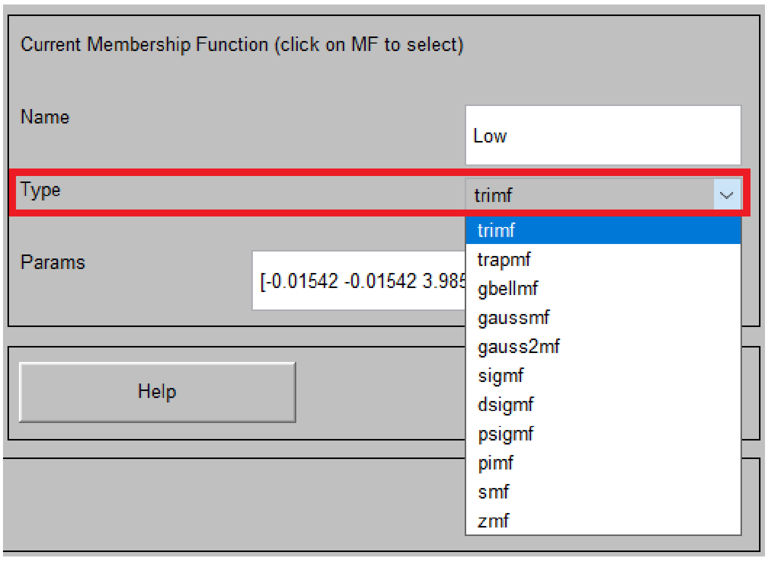
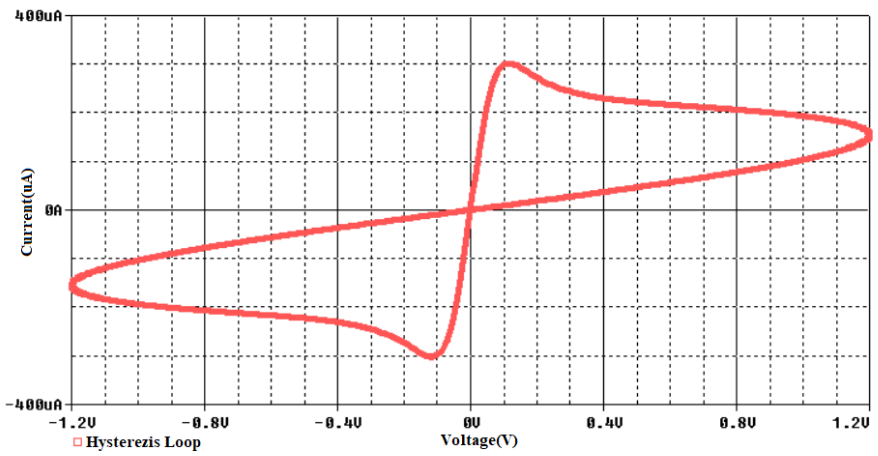


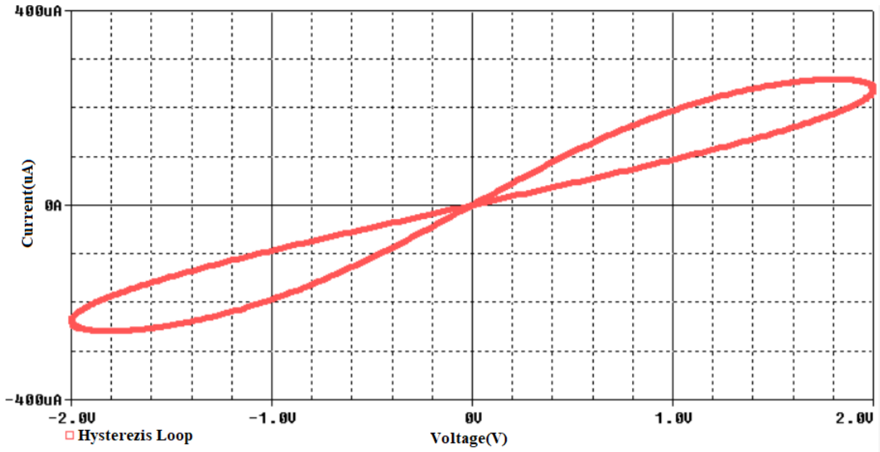
Figure 5. Fuzzy logic probable membership degree functions.

3. Results

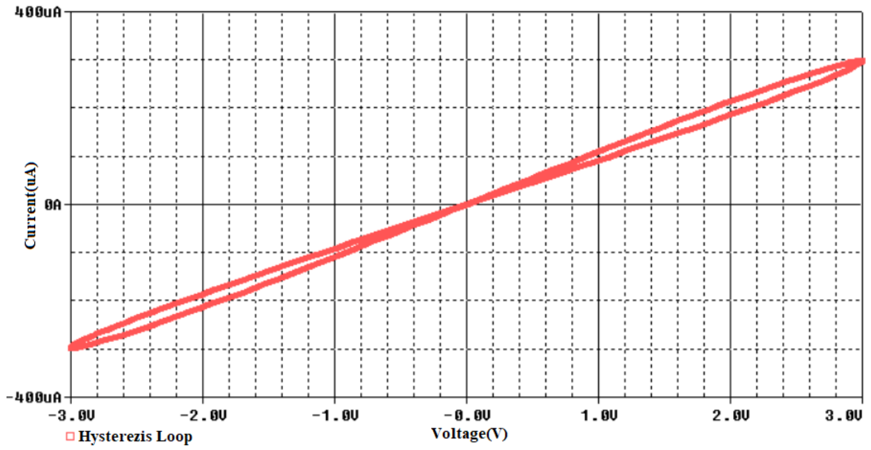
We talked about how the memristor hysteresis curve created by the fuzzy logic method depends on voltage, current and frequency information. Here, we have a single exit against our 3 different inputs. The Joglekar window function used in the study was simulated in LTSPICE using the SPICE model given in (Biolek et al., 2009). Suitable parameter values are shown to create approximately the same hysteresis area with variable current, voltage and frequencies (Figure 6). Memristor parameter values; u_v, D, R_{ON} (low resistance zone) R_{OFF} (high resistance zone) and R_{INITAL} (initial resistance zone) $10^{-10} cm^2 s^{-1} V^{-1}, 10nm, 100\Omega, 16K\Omega$ and $11K\Omega$. The positive correction coefficient for the Joglekar window function was defined as p=10.



a)



b)



c)

Figure 6. Hysteresis fields for different parameters according to the created rule base a) I=300uA, V=1.2V, Frequency=1Hz and Hysterezis area: High (0.816); b) =260uA, V=2V, Frequency=2Hz and Hysterezis Area: High (0.816) and c) I=300uA, V=3V, Frequency=8Hz and Hysterezis area: High (0.816).

In this case, a total of 27 rules were created (Figure 7) (Wen et al., 2018; Görgülü & Bek, 2017). Input variables in this rule table are formed with "and" conjunction with each other to create a single-output response.

1. If (Voltage(V) is Low) and (Current(uA) is Low) and (Frequency(Hz) is Low) then (HysteresisLoop is HighArea) (1)
2. If (Voltage(V) is Low) and (Current(uA) is Low) and (Frequency(Hz) is Middle) then (HysteresisLoop is MiddleArea) (1)
3. If (Voltage(V) is Low) and (Current(uA) is Low) and (Frequency(Hz) is High) then (HysteresisLoop is LowArea) (1)
4. If (Voltage(V) is Middle) and (Current(uA) is Low) and (Frequency(Hz) is Low) then (HysteresisLoop is HighArea) (1)
5. If (Voltage(V) is Middle) and (Current(uA) is Low) and (Frequency(Hz) is Middle) then (HysteresisLoop is MiddleArea) (1)
6. If (Voltage(V) is Middle) and (Current(uA) is Low) and (Frequency(Hz) is High) then (HysteresisLoop is LowArea) (1)
7. If (Voltage(V) is High) and (Current(uA) is Low) and (Frequency(Hz) is Low) then (HysteresisLoop is HighArea) (1)
8. If (Voltage(V) is High) and (Current(uA) is Low) and (Frequency(Hz) is Middle) then (HysteresisLoop is MiddleArea) (1)
9. If (Voltage(V) is High) and (Current(uA) is Low) and (Frequency(Hz) is High) then (HysteresisLoop is LowArea) (1)
10. If (Voltage(V) is Low) and (Current(uA) is Middle) and (Frequency(Hz) is Low) then (HysteresisLoop is HighArea) (1)
11. If (Voltage(V) is Low) and (Current(uA) is Middle) and (Frequency(Hz) is Middle) then (HysteresisLoop is MiddleArea) (1)
12. If (Voltage(V) is Low) and (Current(uA) is Middle) and (Frequency(Hz) is High) then (HysteresisLoop is LowArea) (1)
13. If (Voltage(V) is Middle) and (Current(uA) is Middle) and (Frequency(Hz) is Low) then (HysteresisLoop is HighArea) (1)
14. If (Voltage(V) is Middle) and (Current(uA) is Middle) and (Frequency(Hz) is Middle) then (HysteresisLoop is MiddleArea) (1)
15. If (Voltage(V) is Middle) and (Current(uA) is Middle) and (Frequency(Hz) is High) then (HysteresisLoop is LowArea) (1)
16. If (Voltage(V) is High) and (Current(uA) is Middle) and (Frequency(Hz) is Low) then (HysteresisLoop is HighArea) (1)
17. If (Voltage(V) is High) and (Current(uA) is Middle) and (Frequency(Hz) is Middle) then (HysteresisLoop is MiddleArea) (1)
18. If (Voltage(V) is High) and (Current(uA) is Middle) and (Frequency(Hz) is High) then (HysteresisLoop is LowArea) (1)
19. If (Voltage(V) is Low) and (Current(uA) is High) and (Frequency(Hz) is Low) then (HysteresisLoop is HighArea) (1)
20. If (Voltage(V) is Low) and (Current(uA) is High) and (Frequency(Hz) is Middle) then (HysteresisLoop is MiddleArea) (1)
21. If (Voltage(V) is Low) and (Current(uA) is High) and (Frequency(Hz) is High) then (HysteresisLoop is LowArea) (1)
22. If (Voltage(V) is Middle) and (Current(uA) is High) and (Frequency(Hz) is Low) then (HysteresisLoop is HighArea) (1)
23. If (Voltage(V) is Middle) and (Current(uA) is High) and (Frequency(Hz) is Middle) then (HysteresisLoop is MiddleArea) (1)
24. If (Voltage(V) is Middle) and (Current(uA) is High) and (Frequency(Hz) is High) then (HysteresisLoop is LowArea) (1)
25. If (Voltage(V) is High) and (Current(uA) is High) and (Frequency(Hz) is Low) then (HysteresisLoop is HighArea) (1)
26. If (Voltage(V) is High) and (Current(uA) is High) and (Frequency(Hz) is Middle) then (HysteresisLoop is MiddleArea) (1)
27. If (Voltage(V) is High) and (Current(uA) is High) and (Frequency(Hz) is High) then (HysteresisLoop is LowArea) (1)

Figure 7. Application of emulator circuit built on an electronic.

Optimum output responses were obtained by creating each rule in itself and with its connector. Depending on the fuzzy logic rule, the maximum and minimum values of the membership function are established for the hysteresis curve of the memristor. The window for setting the membership function for the memristor is shown (Figure 8).

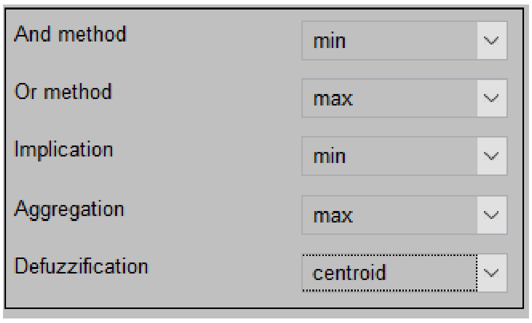


Figure 8. Membership function for memristor hysteresis assessment model.

The distribution of the hysteresis curve according to the rules created in the modeling by using the voltage, current and frequency values is shown (Figure 9) (Tarkhan & Maymandi-Nejad, 2018; Lavanya et al., 2011).

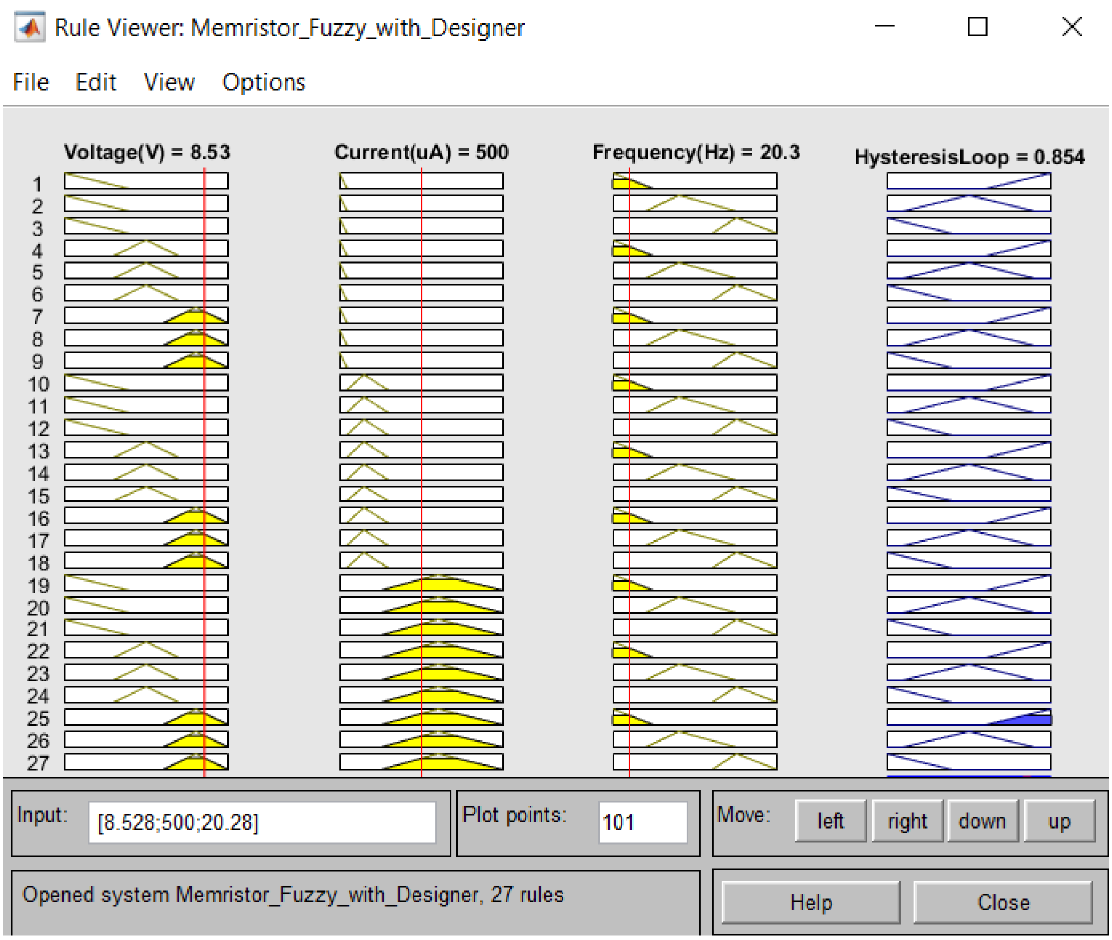


Figure 9. Rules viewers for memristor hysteresis assessment model.

4. Discussion and Conclusion

In this study, optimum parameters for the memristor hysteresis curve are obtained by using fuzzy logic designer. A simulation was carried out by creating 27 fuzzy logic designer rules by using current, voltage and frequency values. If the current, voltage and frequency values are selected outside the boundary conditions determined for the memristor model, it will not show a stable behavior since the necessary condition for the formation of the hysteresis curve cannot be met. In the fuzzy logic designer, firstly, it is divided into three parts as trimf as membership function and low, medium and high as membership degree. When compared with the closest results to this function, it was seen that the best result was obtained with the “trimf” membership degree function. This function provides significant advantages in the precise selection of the hysteresis field boundaries. In the rule base, membership degree points are usually divided into sub-slices between the lowest and highest points. The selection of these regions more or less shows a direct relationship in affecting the success of the system. The linearity of the selected system emerges as the determining factor. Also, the number of parts can be increased further or various optimization methods can be used to find the most ideal membership function. However, the physical parameters of the Joglekar memristor window function are kept constant and the output of the system is handled by leaving the external factors changeable. As a result, it was seen that there is a parallelism between the field calculation of the hysteresis loop and the estimation of the fuzzy logic designer in the Pspice package program. Finally, it was understood that it would be possible to determine the hysteresis field more clearly by using expert systems or artificial intelligence algorithms.

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