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ADVANCED MEMRISTOR MODEL WITH A MODIFIED BIOLEK WINDOW AND A VOLTAGE-DEPENDENT VARIABLE EXPONENT

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Abstract. *The main idea of the present research is to propose a new nonlinear ionic drift memristor model suitable for computer simulations of memristor elements for different voltages. For this purpose, a modified Biolek window function with a voltage-dependent exponent is applied. The proposed modified memristor model is based on Biolek model and due to this and to the use of a voltage-dependent positive integer exponent in the modified Biolek window function it has a new improved property - changing the model nonlinearity extent dependent on the integer exponent in accordance with the memristor voltage. Several computer simulations were made for soft-switching and hard-switching modes and also for pseudo-sinusoidal alternating voltage with an exponentially increasing amplitude and the respective basic important time diagrams, state-flux and i-v relationships are established.*

Keywords: memristor, nonlinear ionic dopant drift, modified Biolek window function, voltage-dependent exponent

ZAAWANSOWANY MODEL MEMRYSTORA ZE MODYFIKOWANYM OKNEM BIOLEK ORAZ EKSPONENTĄ ZALEŻNĄ OD NAPIĘCIA

Streszczenie. *Główną ideą niniejszej pracy jest zaproponowanie nowego modelu nieliniowego dryfu jonowego, odpowiedniego do komputerowych symulacji elementów memrystorowych dla różnych napięć. W tym celu stosowana jest zmodyfikowana funkcja okna Biolek z wykładnikiem zależnym od napięcia. Zaproponowany zmodyfikowany model memrystora oparty jest na modelu Biolek i dzięki temu oraz zastosowaniu zależnego od napięcia dodatniego współczynnika całkowitego w zmodyfikowanej funkcji okna Biolek ma on nową ulepszoną właściwość - zmieniając nieliniową zależność modelu od wykładnika całkowitego zgodnie z napięciem memrystora. Przeprowadzono kilka symulacji komputerowych dla trybów przełączania miękkiego i twardego, a także dla pseudo-sinusoidalnego napięcia przemiennego z wykładniczo rosnącą amplitudą i ustalono odpowiednie podstawowe wykresy czasowe, i zależności stan-strumień oraz prądowo-napięciowe.*

Słowa kluczowe: memrystor, nieliniowy dryft domieszki jonowej, zmodyfikowana funkcja okna Biolek, wykładnik zależny od napięcia

Introduction

The first physical prototype of the memristor element predicted by Leon Chua in 1971 [5] was invented in the HP research labs by Williams in 2008 [9]. It was based on a semiconductor material – crystalline titanium dioxide partially doped with oxygen vacancies [9]. Since this moment a lot of technical papers associated with memristor elements have been written and several basic memristor models have been proposed [1–3, 6, 10]. Each of the most important memristor models is appropriate for specific electrical regimes and applications [1, 10]. The memristor model proposed by Strukov and Williams [9] is with a linear ionic dopant drift and it is appropriate for low voltages and soft-switching mode. The nonlinear ionic drift model of Biolek is able to represent the memristor behaviour for higher voltages and it is mainly used for hard-switching mode [3]. The BCM model [6] and the Generalized BCM [2] memristor model are versatile and they use a switch-based algorithm for representing the boundary effects. They could be used both for soft-switching and hard-switching modes [1, 2, 6]. The Generalized BCM uses sensitivity thresholds not only for the boundaries but for every value of the state variable of the memristor element [2]. The new model proposed in this paper is based on Biolek model. It uses a modified Biolek window function with a voltage-dependent exponent. The new idea of the model proposed here is that the integer exponent of the modified Biolek window function [3] depends on the memristor voltage. Therefore, the respective extent of nonlinearity of the ionic dopant drift dependent on the positive integer exponent used in the window function could be changed in the operation process in accordance with the voltage of the memristor nanostructure. This functionality is very important for the realistic representation of the physical phenomena of the nonlinear ionic dopant drift [1, 2].

The paper is organized as follows. In Section 1 the motivation for creating the new nonlinear drift model, a description of the memristor structure and operation, and the main idea are given. The proposed new memristor model, its description and discussion and the pseudo-code algorithm for the modified memristor model are presented in Section 2. The results obtained by the computer simulations are presented and discussed in Section 3. The concluding remarks are given in Section 4.

1. Background, motivation and basic idea of the new nonlinear memristor model

The modified memristor model proposed here will be discussed using the titanium-dioxide memristor nanostructure described in [9]. The left region of the TiO_2 structure with a length of w is doped with oxygen vacancies [9]. The second sub-layer is made of pure TiO_2. The length of the whole memristor nanostructure is denoted with D [9] The normalized length of the doped layer, also known as the state variable x of the memristor could be defined with the following formula [1, 9]:

$$x = \frac{w}{\mathrm{D}} \tag{1}$$

The equivalent resistance of the memristor element could be expressed using the assumption for a series connection of the doped and the un-doped regions [9] and the substituting circuit of the memristor given in Fig. 1:

$$R = R_{doped} + R_{un-doped} = \mathrm{R_{ON}}x + \mathrm{R_{OFF}}(1-x) \tag{2}$$

where $\mathrm{R_{ON}}$ and $\mathrm{R_{OFF}}$ are the memristances for fully-closed and fully-open states [6, 9, 10], for $x = 1$ or $x = 0$, respectively.

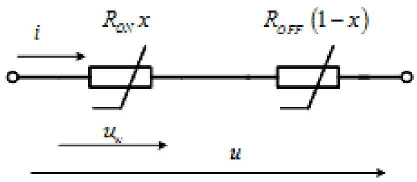

Fig. 1. Substituting circuit of a titanium dioxide memristor

The i-v relationship of the memristor could be expressed using (2) and the state-dependent Ohm's law [4, 9]:

$$u = Ri = \left[\mathrm{R_{ON}}x + \mathrm{R_{OFF}}(1-x)\right]i \tag{3}$$

The voltage drop across the doped region of the memristor element u_w is [7, 9]:

$$u_w = R_{doped}i = \mathrm{R_{ON}}xi = \mathrm{R_{ON}}i\frac{w}{\mathrm{D}} \tag{4}$$

The electric field intensity in the doped layer of the memristor element $\boldsymbol{E}_w$ is [7, 9]:

$$\mathbf{E_w} = \frac{u_w}{w} = i\frac{\mathrm{R_{ON}}}{\mathrm{D}} \tag{5}$$

The rate of moving the boundary between doped and un-doped layers of the element is [7, 9]:

$$v = \frac{\mathrm{d}w}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}(x\mathrm{D}) = \mathrm{D}\frac{\mathrm{d}x}{\mathrm{d}t} = \mu \mathbf{E}_{\mathrm{w}} \tag{6}$$

where μ is the ionic dopant drift mobility [7, 9]. After transformations of (6) the basic differential equation of the memristor is derived [2, 6, 9]:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \frac{\mu \mathrm{R}_{\mathrm{ON}}}{\mathrm{D}^2} i = \mathrm{k}i \tag{7}$$

where k is a constant dependent on the memristor parameters. When we have two or more memristors in a circuit then formula (7) must be modified [6, 10]:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \eta \frac{\mu \mathrm{R}_{\mathrm{ON}}}{\mathrm{D}^2} i = \eta \mathrm{k}i \tag{8}$$

where η is a polarity coefficient [6, 10]. When the memristor element is forward-biased we have η = 1. For a reverse-biased memristor the polarity coefficient is η = -1 [6].

Formula (8) is valid only for very small electrical currents and memristor voltages [1, 6, 9]. For representing the nonlinear ionic drift effect in the general case an additional window function is needed to be used in the right side of (8) [1, 3]:

$$f_B(x,i) = 1 - [x - stp(-i)]^{2\mathrm{p}} \tag{9}$$

where p is a positive integer exponent. The function expressed with (9) is presented for first use by Biolek in [3] and it is also known as a Biolek window function [3].

Then the state equation of the memristor element presented with (8) could be modified using (9) and according to [3] is:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \eta \mathrm{k}i f_B(x,i) = \eta \mathrm{k}i\left\{1 - [x - stp(-i)]^{2\mathrm{p}}\right\} \tag{10}$$

where $f_B(x)$ is the original Biolek window function [3]. The function *stp(i)* used in (9) and (10) is [3]:

$$stp(i) = \begin{cases} 1, \ if \ i \ge 0 \ (u \ge 0) \\ 0, \ if \ i < 0 \ (u < 0) \end{cases} \tag{11}$$

After substitution of (11) in (10) the following equations are derived [3]:

$$\begin{aligned} \frac{\mathrm{d}x}{\mathrm{d}t} &= \eta \mathrm{k}i\left[1 - (x-1)^{2\mathrm{p}}\right], \ u(t) \le 0, \ [i(t) \le 0] \\ \frac{\mathrm{d}x}{\mathrm{d}t} &= \eta \mathrm{k}i\left[1 - x^{2\mathrm{p}}\right], \ u(t) > 0, \ [i(t) > 0] \end{aligned} \tag{12}$$

The original Biolek memristor model discussed here is fully described with equations (3) and (12).

2. The proposed modified new memristor model description and pseudo-code based algorithm

If the memristor voltage increases then the ionic dopant drift nonlinearity increases too [1, 3, 10]. Practically the representation of the increasing the nonlinearity of the ionic dopant drift could be expressed with decreasing of the positive integer exponent in the Biolek window function [1, 3, 6]. The projected relationship between the positive integer exponent of the modified Biolek window function in the proposed memristor model and the absolute value of the memristor voltage could be expressed approximately with a hyperbolic-like function:

$$p = round\left(\frac{10}{|u|+1}\right) \tag{13}$$

where the function '*round*' is used for deriving an integer result. Then the modified Biolek window function $f_{BM}(x,u)$ used in the proposed memristor model is:

$$\begin{aligned} f_{BM}(x,u) &= 1 - (x-1)^{2round\left(\frac{10}{|u|+1}\right)}, \ u(t) \le 0 \\ f_{BM}(x,u) &= 1 - x^{2round\left(\frac{10}{|u|+1}\right)}, \ u(t) > 0 \end{aligned} \tag{14}$$

Then the proposed memristor model could be fully described using the following equations:

$$\begin{aligned} \frac{\mathrm{d}x}{\mathrm{d}t} &= \eta \mathrm{k}i\left[1 - (x-1)^{2round\left(\frac{10}{|u|+1}\right)}\right], \ u(t) \le 0, \ [i(t) \le 0] \\ \frac{\mathrm{d}x}{\mathrm{d}t} &= \eta \mathrm{k}i\left[1 - x^{2round\left(\frac{10}{|u|+1}\right)}\right], \ u(t) > 0, \ [i(t) > 0] \\ u &= Ri = \left[\mathrm{R}_{\mathrm{ON}}x + \mathrm{R}_{\mathrm{OFF}}(1-x)\right]i \end{aligned} \tag{15}$$

where the third equation in (15) is (3) and it represents the state-dependent Ohm's Law for the memristor element [9]. Using (15) and the finite differences method [4] a pseudo-code based algorithm is derived for the computer simulations:

A pseudo-code based algorithm of the proposed model

```
% memristor parameters and voltage characteristics
eta=1; um=0.5; f=40; psiu=deg2rad(-60);
Ron=100; Roff=16000; deltaR=Ron-Roff; mu=1e-12;
D=10e-9; k=(mu*Ron)/(D^2); x0=0.3; xmin=0; xmax=1;
% the function "sine_gen" is used for generating a sinusoidal
% voltage signal
[u,t,deltat,tmin,tmax,N]=sine_gen(um,f,psiu);
% the function "integr" is used for obtaining the magnetic flux
% linkage using the voltage signal
n=1:1:N+1; flux=integr(u,deltat,tmin,tmax);
% the function "biolekvar1" is used for simulation using the
 modified Biolek memristor model
[x,biolekwin,p]=biolekvar1(deltat,u,k,eta,deltaR,Roff,x0,N);
% the function "biolekvar3" is used for simulation using the
original Biolek memristor model
[z,biolekwin3]=biolekvar3(deltat,u,k,eta,deltaR,Roff,x0,N);
Req=deltaR*x+Roff; Req2=deltaR*z+Roff;
iM=u./Req; iM2=u./Req2;
function [u,t,deltat,tmin,tmax,N]=sine_gen(um,f,psiu)
% Steady state sine analysis
T=1/f; tmin=0; tmax=8*T; deltat=(tmax-tmin)/1e5;
t1=tmin:deltat:tmax; omega=2*pi*f;
f1=um*sin(omega*t1+psiu);
%f1=um*exp(2.5*t1).*sin(omega*t1+psiu);
u=f1; t=t1; N=tmax/deltat; End
function psi=integr(u,deltat,tmin,tmax)
N=(tmax-tmin)/deltat; % number of samples
n=1:1:N+1; % sample vector
psi=[ ]; % empty array for the flux linkage
% integrating u with respect to t
for n=1;   psi1(n)=0; end
for n=2:1:N+1;    psi1(n)=psi1(n-1)+u(n-1)*deltat;
end; psi=[psi psi1]; end
function [x,biolekwin,p] =biolekvar1(deltat,u,k,eta,
deltaR,Roff ,x0,N); p=[ ]; x=[ ]; biolekwin=[ ];
for n=1,    x1=x0;    biolekwin1=1;
   p1(n)=round(10./(abs(u(n))+1));
end; for n=2:1:N+1;
   p1(n)=round(10./(abs(u(n))+1));
   A=deltaR*x1(n-1)+Roff;
   if u(n)<=0
   x1(n)=x1(n-1)+(eta*k*u(n-1)*deltat*(1-(x1(n-1)-
1).^(2*p1(n)))))/A;
   biolekwin1(n)=1-(((x1(n)-(sign(-u(n))+
1)/2)).^(2*p1(n)));       else
      x1(n)=x1(n-1)+(eta*k*u(n-1)*deltat*(1-(x1(n-
1)).^(2*p1(n)))))/A;
      biolekwin1(n)=1-(((x1(n)-(sign(-u(n))+1)/2)).^
(2*p1(n)));       end end    p=[p p1];    x=[x x1];
   biolekwin=[biolekwin biolekwin1]; end
function [x, biolekwin]=biolekvar3 (deltat,u,k,eta,
deltaR, Roff, x0,N); x=[ ]; biolekwin=[ ]; for n=1    x1=x0;
   biolekwin1(n)=1-(((x1(n)-(sign(-u(n))+1)/2)).^(2*1));
```

```
end for n=2:1:N+1;     A=deltaR*x1(n-1)+Roff;
    if u(n)<=0,     x1(n)=x1(n-1)+(eta*k*u(n-1)*deltat
*(1-(x1(n-1)-1)^(2*1)))/A;
    biolekwin1(n)=1-(((x1(n)-(sign(-u(n))+1)/2)).^(2*1));
    else x1(n)=x1(n-1)+(eta*k*u(n-1)*deltat
    *(1-(x1(n-1))^(2*1)))/A;
    biolekwin1(n)=1-(((x1(n)-(sign(-u(n))+1)/2)).^(2*1));
    end end   x=[x x1];  biolekwin=[biolekwin biolekwin1];
   end procedure
```

3. Simulations results

3.1. Soft-switching mode

The computer simulations of the memristor models were made in MATLAB environment [8, 10]. Here we will make a comparison of several results obtained by the use of the original Biolek memristor model and the proposed modified Biolek model. The voltage signal for testing the memristor is: $u(t) = 0.6 \cdot \sin(2 \cdot \mathrm{pi} \cdot 40 \cdot t - 60°)$. The time diagrams of the memristor voltage and the respective value of the integer positive exponent are presented in Fig. 2. In this case the integer exponent p changes in the range from 6 to 10 in accordance to the absolute value of the memristor voltage.

The state-flux relationships of the memristor according to the original Biolek model and the proposed modified model are shown in Fig. 3. According to the original Biolek memristor model the state-flux relatioship is a multi-valued curve while fo the same conditions the state-flux relationship of the modified memristor model is almost a single-valued curve which is an advantage of the proposed modified memristor model. The time diagrams of memristor current according to the original Biolek model and the proposed model are presented in Fig. 4. For both the memristor models the current has a non-sinusoidal form due to the memristor nonlinearity. The current-voltage relationships of the memristor element according to the original Biolek memristor model and the proposed modified Biolek memristor model are given in Fig. 5. It is clear that the current-voltage relationships are pinched hysteresis loops both for the original Biolek model and for the proposed modified Biolek memristor model and they almost coincide to each other. For the original Biolek model the i-v relation is a multi-valued curve while for the proposed model it is almost a double-valued curve.

The diagrams of the original Biolek window function $f_B\ (x,u)$ and of the modified Biolek window function $f_{BM}(x,u)$ derived respectively for the original Biolek memristor model for different values of the positive integer exponent p and for the modified Biolek model with a voltage-dependent exponent are shown in Fig. 6. The range of the state variable for the original Biolek model increases with the growing of the integer exponent p while in the same time the range of the window function decreases. For exponents higher than 1 the original Biolek window function reaches its maximal value of 1. With increasing the positive integer exponent in the original Biolek window function the ionic dopant drift nonlinearity extent decreases.

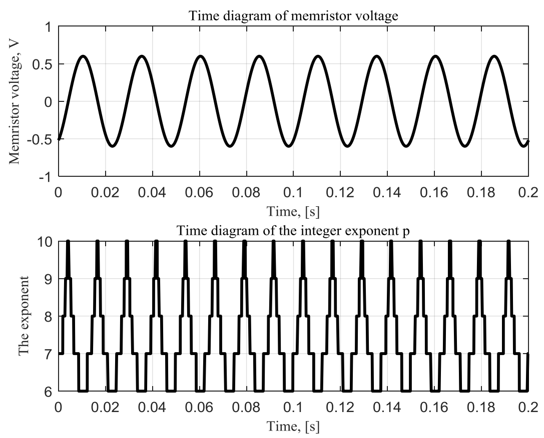

Fig. 2. Time diagrams of memristor voltage and the integer exponent p in the modified Biolek window function for soft-switching mode

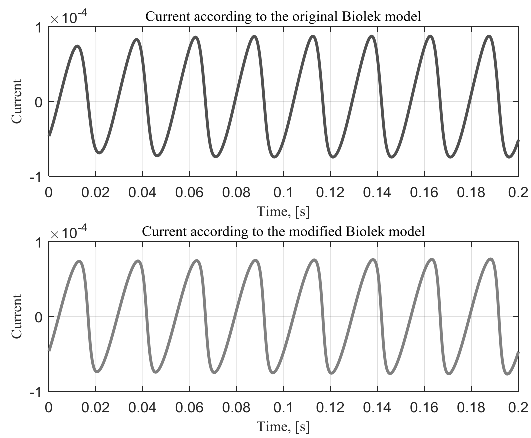

Fig. 4. Time diagrams of memristor current according to the original Biolek memristor model and the modified Biolek model for soft-switching mode

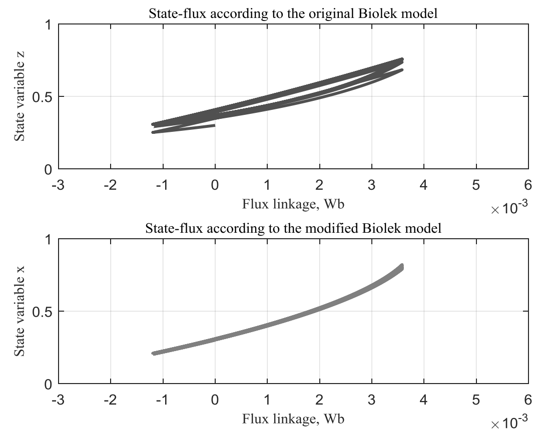

Fig. 3. State-flux relationships of the memristor according to the original Biolek memristor model and the modified Biolek model for soft-switching mode

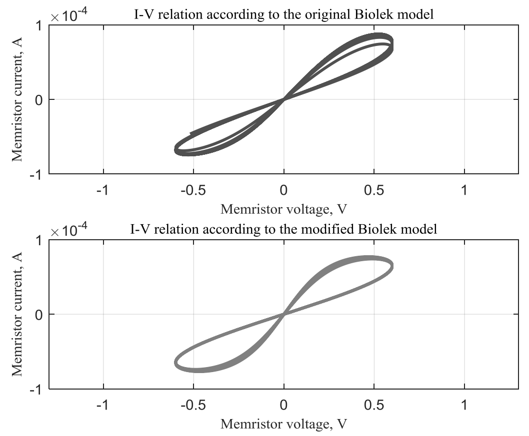

Fig. 5. I-V relationships of the memristor according to the original Biolek memristor model and the modified Biolek model for soft-switching mode

After a comparison of the original Biolek window function for different values of the positive integer exponent *p* with the proposed modified window function it could be concluded that the modified Biolek window function is created from several segments taken from the original Biolek window functions obtained for different positive exponents *p*. According to the proposed modified memristor model the positive integer exponent *p* changes automatically in the simulation process in dependence with the absolute value of the memristor voltage and the operating point of the memristor in the field of the relationship between the modified window function and the state variable *x* is moving on several different segments for different exponents *p*.

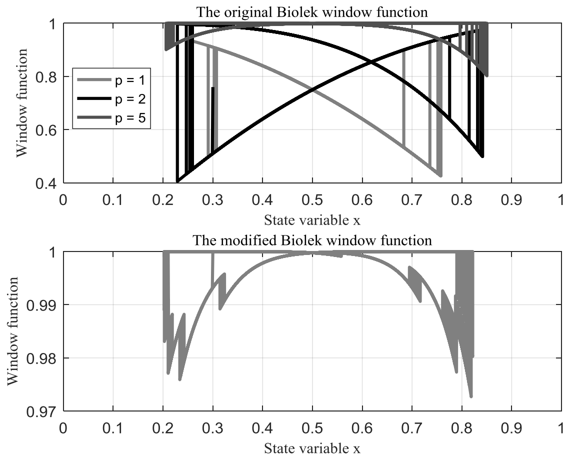

Fig. 6. Diagrams of the window functions according to the original Biolek memristor model and the modified Biolek model for soft-switching mode

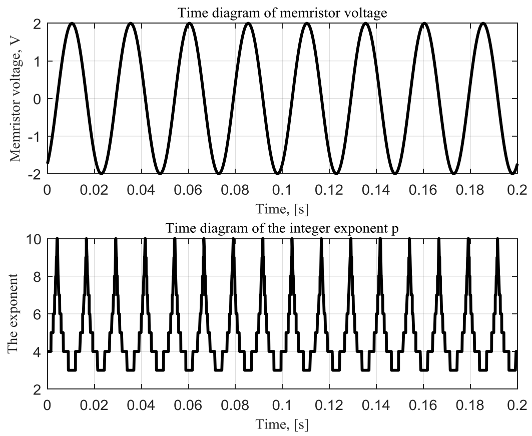

Fig. 7. Time diagrams of memristor voltage and the integer exponent p in the modified Biolek window function for hard-switching mode

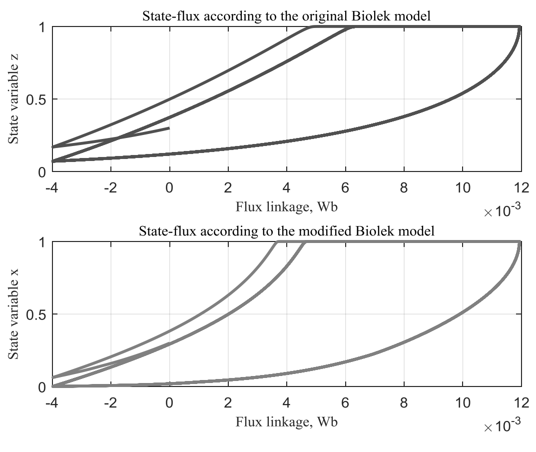

Fig. 8. State-flux relationships according to the original Biolek memristor model and the modified Biolek model for hard-switching mode

3.2. Hard-switching mode

The voltage signal used for the computer simulations in a hard-switching mode is: $u(t) = 2\cdot\sin(2\cdot\mathrm{pi}\cdot 40\cdot t - 60°)$. The time diagrams of the memristor voltage and the respective integer positive exponent of the modified Biolek window function are represented in Fig. 7. In the case of hard-switching mode the exponent *p* changes in a larger range (from 3 to 10) than the respective range for soft-switching mode (from 6 to 10) and the respective nonlinearity extent of the ionic drift is higher.

The respective state-flux relationships of the memristor for the original Biolek model and for the proposed modified Biolek model are presented in Fig. 8. It is clear that both the original Biolek model and its modification are able to limit the state variable in the range (0, 1). For the original Biolek memristor model in this case the state variable *x* does not reach the minimal limit of 0 but for the modified memristor model this limit is almost reached.

The time diagrams of the memristor currents according to the original Biolek model and the proposed modified Biolek model are presented in Fig. 9. In both the cases the memristor operates as a rectifying semiconductor diode. According to the proposed memristor model the current maximal value is a little bit higher than the respective maximal value for the original Biolek memristor model.

The current-voltage relationships of the memristor element obtained according to the original Biolek memristor model and the proposed modified Biolek model are presented in Fig. 10. In both the cases the current-voltage relationship is an anti-symmetrical curve and it confirms the rectifying behaviour of the memristor element when it operates in a hard-switching mode [6]. In the present case the respective current-voltage relationships almost match to each other.

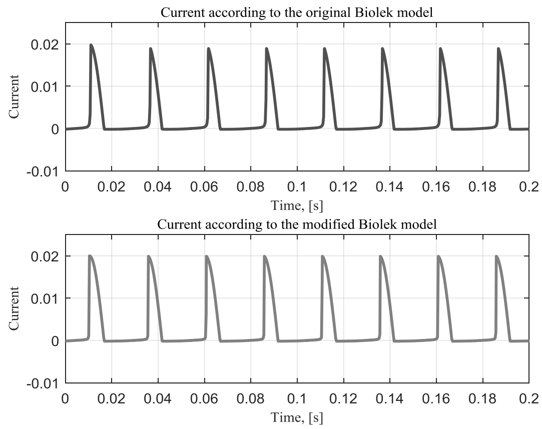

Fig. 9. Time diagrams of memristor current according to the original Biolek memristor model and the modified Biolek model for hard-switching mode

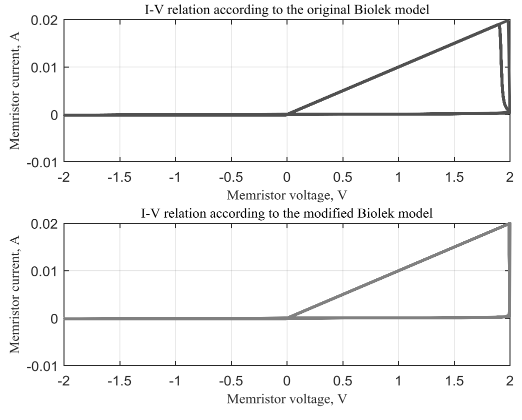

Fig. 10. I-V relationships of the memristor according to the original Biolek memristor model and the modified Biolek model for hard-switching mode

The diagrams of the original Biolek window functions for different positive integer exponents *p* and the modified Biolek window function are presented in Fig. 11. For the original Biolek memristor model if the exponent *p* is higher than 2 the state variable and the window function have their maximal range – from 0 to 1. This phenomenon is also derived for the proposed modified Biolek model for this case. For the original Biolek model the nonlinearity of the model is fixed and the integer exponent p has a value of 1, 2 or 5, while for the modified Biolek model the nonlinearity extent depends on the memristor voltage. Due to the full range of the state variable (from 0 to 1) the hard-switching behaviour of the memristor element is more clearly expressed by the use of the modified Biolek memristor model.

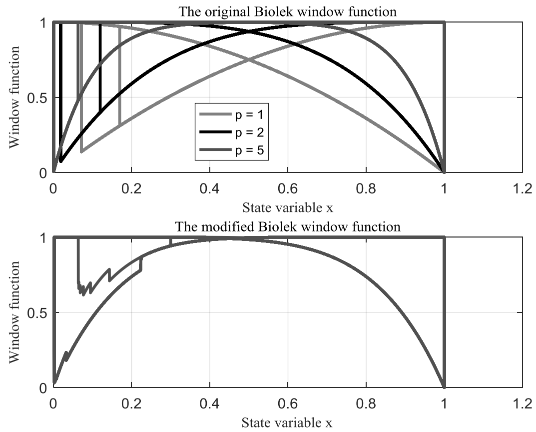

Fig. 11. Diagrams of the window functions according to the original Biolek memristor model and the modified Biolek model for hard-switching mode

3.3. Analysis of the proposed modified memristor model for AC voltage signal with an exponentially increasing magnitude

In this paragraph for testing the proposed modified memristor model we use an AC voltage signal with exponentially increasing magnitude. In this case we could observe the transition between the soft-switching mode and hard-switching mode it the time domain. The voltage signal used for the computer simulations is as follows: $u(t) = 0.6 \cdot \exp(3 \cdot t) \cdot \sin(2 \cdot \mathrm{pi} \cdot 40 \cdot t - 60°)$. The time diagrams of the pseudo-sinusoidal memristor voltage and the respective integer exponent of the modified Biolek window function are presented in Fig. 12. It is easy to observe the change of the exponent range which depends on the voltage. The state-flux relation of the memristor obtained by the use of the original Biolek memristor model and the modified Biolek model are presented in Fig. 13. In both the cases the state-flux relationships are obtained as a multi-valued hysteresis curves. The time diagrams of the memristor currents for the original Biolek memristor model and for the proposed modified Biolek model are presented in Fig. 14. For the original Biolek model the memristor current is with very low level and in the end of the simulation interval the current amplitude increases and the element starts operation in a hard-switching mode. For the proposed modified Biolek memristor model the memristor current is obtained with a magnitude several times higher than the current amplitude derived by the original Biolek model. The current-voltage relationships of the memristor according to the original Biolek model and to the proposed modified model for a pseudo-sinusoidal voltage signal with an exponentially increasing amplitude are presented in Fig. 15. Observing the current-voltage curves one can determine the transition between the soft-switching and hard-switching modes.

For given conditions the soft-switching behaviour is dominating for the original Biolek model while the hard-switching mode is more clearly expressed for the proposed modified Biolek model. The window functions for the original Biolek memristor model for several different positive integer exponents and for the modified memristor model are presented in Fig. 16. In this case the extent of ionic drift nonlinearity for the modified Biolek memristor model changes in the simulation process while for the original Biolek model the integer exponent is fixed. The nonlinearity extent of the ionic dopant drift decreases if we choose a higher value of the positive integer exponent.

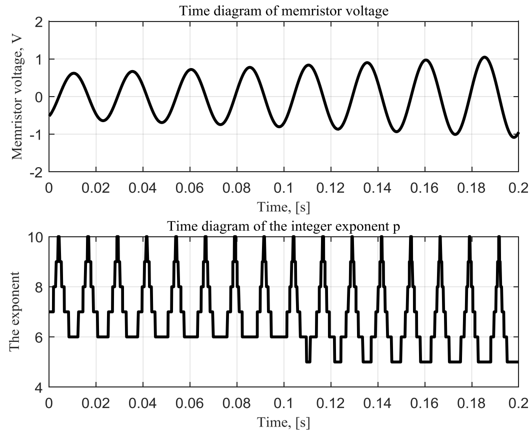

Fig. 12. Time diagrams of the voltage u and the integer exponent p for pseudo-sinusoidal voltage with an exponentially increasing magnitude

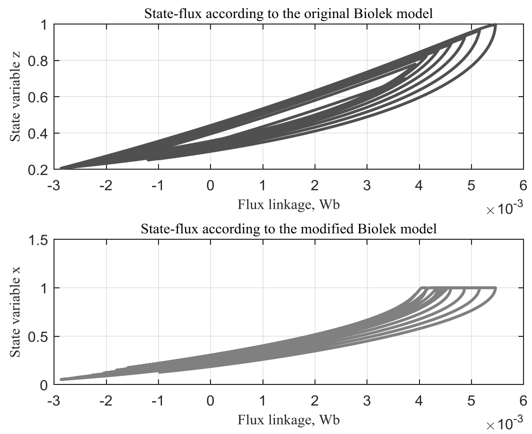

Fig. 13. State-flux relations of the memristor according to the original Biolek memristor model and the modified Biolek model for pseudo-sinusoidal voltage with an exponentially increasing magnitude

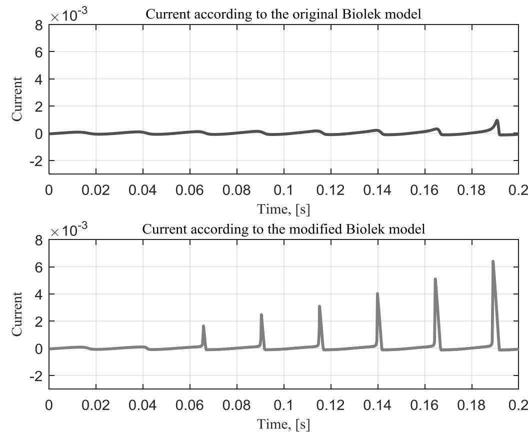

Fig. 14. Time diagrams of the memristor current according to the original Biolek model and the modified Biolek model for pseudo-sinusoidal voltage with an exponentially increasing amplitude

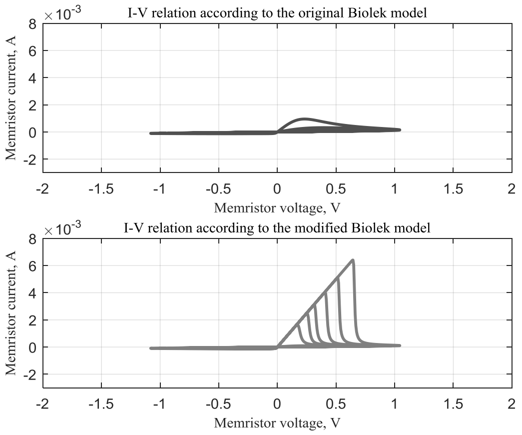

Fig. 15. Current-voltage relationships of the memristor according to the original Biolek memristor model and the modified Biolek model for pseudo-sinusoidal voltage with an exponentially increasing amplitude

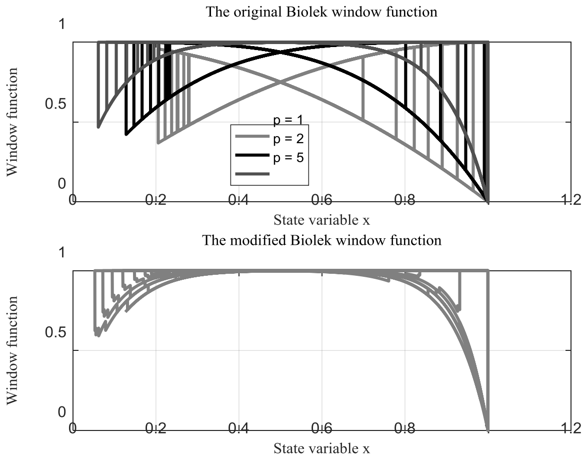

Fig. 16. Window functions diagrams according to the original Biolek memristor model and the modified Biolek memristor model for pseudo-sinusoidal voltage signal with an exponentially increasing magnitude

If we observe the window functions for the original Biolek memristor model presented in the first sub-figure of Fig. 16 then it could be concluded that for the given circumstances if we increase the integer exponent p then the state variable tends to reach its minimal value of 0. The proposed modified window function presented in the second sub-figure of Fig. 16 is derived by the use of several segments of the original Biolek window functions for different positive integer exponents. This phenomenon is based on the proposed relationship between the positive integer exponent p and the absolute value of the memristor voltage.

4. Conclusion

After the detailed analytical description and the computer simulations of the proposed modified Biolek memristor model in parallel with the original Biolek model investigation several conclusions could be completed. The new modified nonlinear memristor model proposed in this research is based on the Biolek model. It has many of the advantages of the original Biolek memristor model. The proposed model has a nonlinear ionic dopant drift and a mechanism for limitation of the state variable in the range from 0 to 1 confirmed by simulations for hard-switching mode. The new model has a new advantage with respect to the original Biolek model with fixed integer exponent – the ability for realistic representation of ionic dopant drift nonlinearity in accordance to the absolute value of the applied memristor voltage. As it could be seen from the simulation results the state-flux relationships of the modified Biolek model for soft-switching are almost single-valued curves which is an advantage of the new model with respect to the original Biolek model which represents for the same condition multi-valued state-flux relationships of the memristor element.

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