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Research Article

A Novel Generalized Memristor Based on Three-Phase Diode Bridge Rectifier

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Memristive characteristics in three-phase diode bridge rectifier circuit are proposed in this paper. The conduction of the diodes is discussed and the characteristics of the pinched hysteresis loop are analyzed by both numerical simulations and circuit simulations. The hysteresis loops of each phase not only are pinched at the origin but also have the other two intersection points in the first quadrant and the third quadrant when three-phase bridge rectifier circuit is running under normal operation. Other conditions are also discussed when a variety of faults conditions occur. The simulation results verify that the three-phase bridge rectifier circuit can be described as a generalized memristor element during several operation states.

1. Introduction

It has been proved that memristive characteristics exist in many systems [1, 2]. Since the discovery of the memristor, it has been widely used in neuromorphic circuits [3], nonvolatile information storage [4], chaotic systems and oscillators [5, 6], and other applications. In recent years, the research of generalized memristor has aroused wide interest of the scholars. A class of diode bridge circuits has been analyzed because of the memristive characteristics [7–14]. A simple electronic circuit which only consists of four diodes and a second-order RLC filter was proved to have memory properties [7]. By replacing the second-order RLC filter with a first-order parallel RC filter, another equivalent realization circuit of a generalized memristor was implemented, which decreases a fundamental circuit element-inductor [8, 9]. Meanwhile, a diode bridge circuit with a series first order RL filter also satisfies the definition of an ideal memristor; as a result, it can be described as a generalized memristor as well [10]. After that, a modified diode bridge circuit cascaded with a second-order filter containing an inductor and a capacitor was proposed and was proved to constitute a generalized memristor [11]. Recently, an improved memristive diode bridge circuit was put forward comprising four diodes and an inductor, which has a much simpler circuit realization [12, 13]. On the basis of the fractional calculus theory, a fractional-order capacitor-based diode bridge circuit was proposed, in which the fractional order capacitor is circuit implemented utilizing Oustaloup approximation technique [14].

Since a single-phase diode bridge rectifier circuit can express the memristive features, does a three-phase diode bridge rectifier circuit have the same characteristics? In this paper, a diode bridge circuit which contains six diodes and a parallel first order RC filter is proposed, and the input voltage of such circuit is three-phase voltage which has the same amplitude and frequency; phase difference of each phase is 120 degrees. In order to study whether a three-phase diode bridge rectifier circuit can be regarded as a generalized memristor under several operating conditions, in Section 2, we theoretically analyze the conduction conditions of six diodes in three-phase diode bridge rectifier circuit under different operating conditions. And the relation curves between input voltages and input currents are given by numerical simulations and circuit simulations. Conclusions are given in Section 3.

Table 1: Conduction situations of six diodes.

Time interval	I	II	III	IV	V	VI
Conducting diodes	VD_1, VD_6	VD_1, VD_2	VD_3, VD_2	VD_3, VD_4	VD_5, VD_4	VD_5, VD_6
Input voltage relation	$u_a > u_c > u_b$	$u_a > u_b > u_c$	$u_b > u_a > u_c$	$u_b > u_c > u_a$	$u_c > u_b > u_a$	$u_c > u_a > u_b$

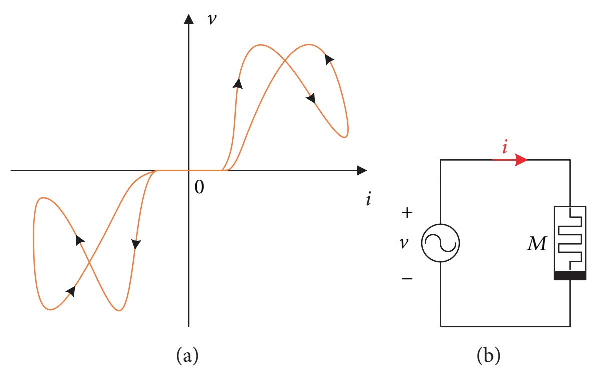

Figure 1: The definition of a voltage-controlled ideal memristor. (a) Hysteresis loop of a memristor. (b) The symbol of a memristor.

2. Three-Phase Bridge Rectifier Circuit Running under Several Conditions

Equipment can be described as a voltage-controlled ideal memristor when a periodic voltage is applied to two terminals of the equipment, and the current response is periodic and has the same frequency [15]. Besides, the locus in the v-i plane invariably passes through the origin; the current flowing through the device is always zero when the input voltage is zero, as shown in Figure 1(a). The other two essential characteristics of a memristor are the facts that the areas of the hysteresis loops decrease monotonically as the frequency increases when frequency is greater than a critical value and the pinched hysteresis loop will shrink to a nonlinear single-valued function when the frequency tends to infinite [16].

2.1. Running under Normal Condition. Consider six diodes and a parallel RC filter constituted a three-phase diode bridge rectifier circuit, which is depicted in Figure 2. When the circuit is running under normal condition, the input voltages are given as $u_a = 8\sin(2\pi ft)$, $u_b = 8\sin(2\pi ft - 2\pi/3)$, and $u_c = 8\sin(2\pi ft - 4\pi/3)$, and suppose the conduction voltage of the diode is zero; the conduction situations of six diodes in one cycle are shown in Table 1.

It can be seen that only two diodes are conductive at the same time, which is similar to single-phase diode bridge circuit proposed in [8]. As a result, the input current of **a** phase can be derived from the mathematical model of the single-phase diode bridge circuit, which is written as

$$i_a = 2I_S e^{-\rho u_d}\sinh(\rho u_{in}) \quad (1)$$

where $\rho = 1/(2nV_T)$; I_S, n, and V_T indicate the reverse saturation current, emission coefficient, and thermal voltage

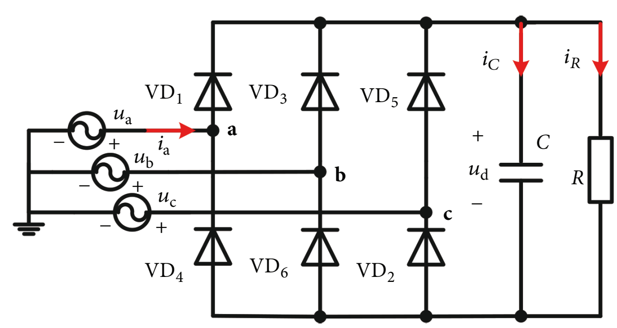

Figure 2: Three-phase diode bridge rectifier circuit.

of the diode, respectively. u_{in} expresses the input voltage of circuit under different circumstances, which can be shown as

$$u_{in} = \begin{cases} u_a - u_b : u_a > u_c > u_b \\ u_a - u_c : u_a > u_b > u_c \\ u_b - u_a : u_b > u_c > u_a \\ u_c - u_a : u_c > u_b > u_a \\ 0 : u_c > u_a > u_b \\ 0 : u_b > u_a > u_c \end{cases} \quad (2)$$

And u_d represents the voltage across capacitor C, which can be calculated by

$$\frac{du_d}{dt} = \frac{2I_S\left(e^{-\rho u_d}\cosh(\rho u_{in}) - 1\right)}{C} - \frac{u_d}{RC} \quad (3)$$

Thus, the mathematical model of three-phase diode bridge circuit is established, and numerical simulation can be carried out in MATLAB. Circuit parameters used for numerical simulation are given in Table 2. Figure 3 represents the input

Table 2: Circuit parameters for numerical simulation.

Parameters	Significations	Values
I_S	Reverse saturation current of diode	2.682 nA
n	Emission coefficient of diode	1.836
V_T	Thermal voltage of diode	25 mV
R	Resistance	10 kΩ
C	Capacitance	1 uF
f	Frequency	50 Hz

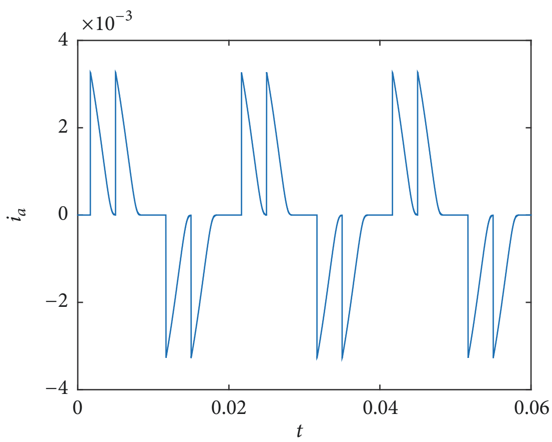

Figure 3: Input current of a phase with time t.

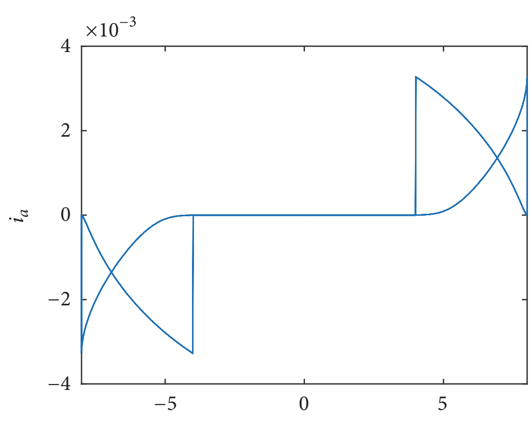

Figure 4: Locus in $u_a - i_a$ plane.

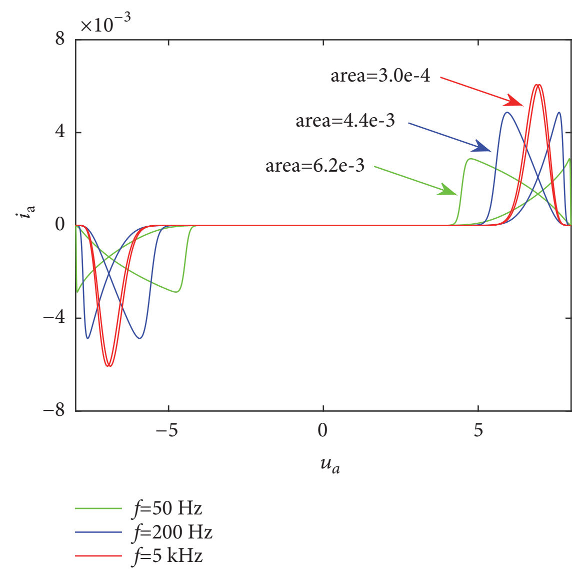

Figure 5: Curves of input voltage u_a and input current i_a.

current of **a** phase with time t, and the relation curve between input voltage u_a and input current i_a is shown in Figure 4. It can be seen that the locus in $u_a - i_a$ plane is hysteresis loop and is pinched at the origin. Besides, the trajectory is intersecting in the first quadrant and the third quadrant.

Then we consider using PSpice to carry out circuit simulations in order to verify whether one phase can be described as a generalized memristor. Diodes in the three-phase rectifier bridge are chosen as 1N4148 and parameters of the resistor and the capacitor in first order parallel RC filter are set as in Table 2. Figure 5 shows the relation curves of input voltage and input current in **a** phase with the different three-phase input voltage frequencies. Because the input voltage is three-phase input voltage, the frequency of each phase is changed at the same time. When the frequency is greater than the critical value, the areas of the hysteresis loops decrease monotonically as the frequency increases and what we can see in Figure 5 is that the hysteresis loop almost shrinks to a nonlinear single-valued function when $f = 5$kHz. In addition, it can be seen that the hysteresis loops not only are pinched at the origin but also have the other two intersection points in the first quadrant and the third quadrant. The described hysteresis loops satisfy the three essential features of a memristor; as a result, it can be regarded as a generalized memristor. Because the input voltage has only difference in phase, the curves of input voltage and input current in **b** phase and **c** phase are the same as **a** phase; each phase of the three-phase diode bridge rectifier circuit can be known as an ideal memristor when the circuit is running under normal operation and input voltage is three-phase voltage (three-phase voltage has the same frequency and phase difference is 120 degrees).

2.2. Running under Single-Phase Short-Circuit Condition. Consider three-phase bridge rectifier circuit is running under single-phase short-circuit condition; the equivalent circuit

Table 3: Conduction situations of six diodes.

Time interval	I	II	III	IV
Conducting diodes	VD_1, VD_6	/	VD_3, VD_4	/
Input voltage relation	$u_a > u_{C^+} > u_b$	$u_{C^+} \geq u_a$ (or u_b)	$u_b > u_{C^+} > u_a$	$u_{C^+} \geq u_b$ (or u_a)

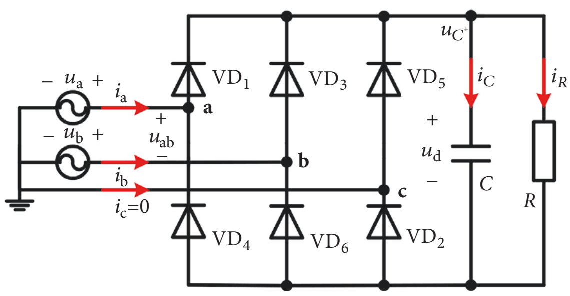

Figure 6: Three-phase bridge rectifier circuit running under single-phase short-circuit condition.

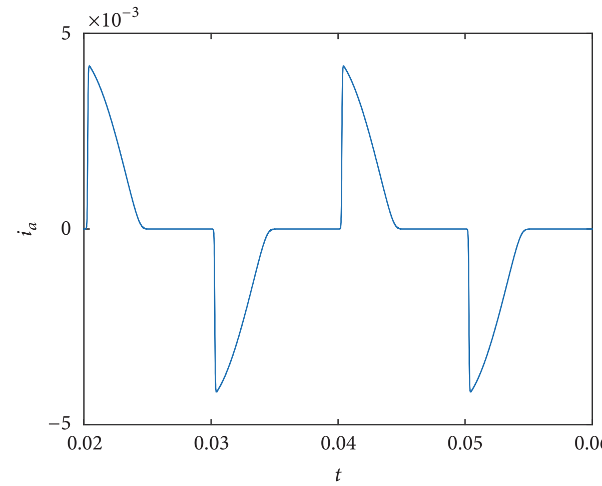

Figure 7: Input current of **a** phase versus time t.

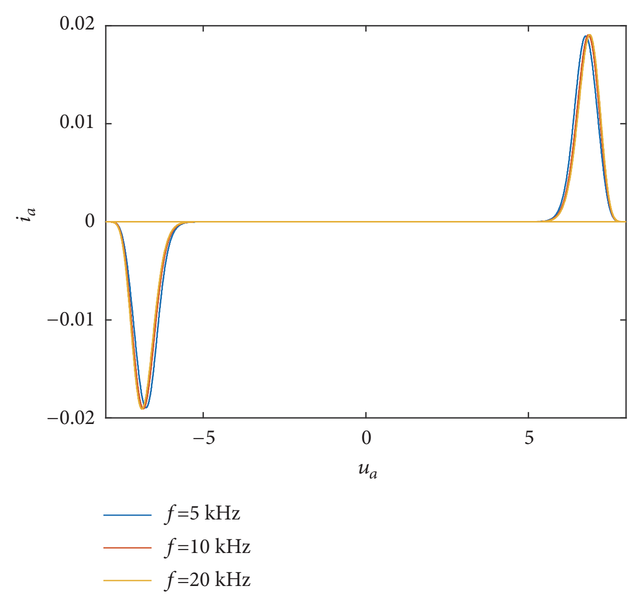

Figure 8: Loci in v-i plane.

can be described as in Figure 6. The voltage between **a** phase and **b** phase is depicted as u_{ab} and u_{C^+} indicates the voltage value at the positive terminal of the capacitor C. In Figure 6, **a** phase and **b** phase are running in normal operation, while **c** phase is connected to the ground because of short circuit. Set the input voltage as $u_a = 8\sin(2\pi ft)$, $u_b = 8\sin(2\pi ft - 2\pi/3)$, and assume the conduction voltage of the diode is zero; the conduction situations of six diodes in one cycle are shown in Table 3.

It can be seen that, at the beginning, the input voltage charges to the capacitor, diodes VD_1 and VD_6 break over, and when the input voltage is less than the capacitor voltage value at the positive terminal, the capacitor discharges, the six diodes switch off, and the currents that flow through six diodes are zero. By the way, diodes VD_2 and VD_5 are turned off all the time; the current flowing through **c** phase is zero. Therefore, the mathematical model of input current in **a** phase when the three-phase diode bridge circuit is running under single-phase short-circuit condition is similar to that of the single-phase diode bridge circuit proposed in [8], which can be written as

$$i_a = 2I_S e^{-\rho u_d} \sinh(\rho u_{ab}) \tag{4}$$

Take the same parameters as in Table 2; the input current of **a** phase versus time t can be described in Figure 7, and the loci of u_a vs. i_a in v-i plane with different frequencies can be depicted in Figure 8. When f is set to 5 kHz, to 10 kHz, and to 20 kHz, the curves of input voltage u_a and input current i_a are almost coincident, which do not accord with the three fingerprints of a memristor; as a result, it cannot be considered as a generalized memristor.

Then we consider **a** phase to be the input terminal and **b** phase to be the output terminal, and the voltage difference between **a** phase and **b** phase can be calculated as $u_{ab} = u_a - u_b = 16\sin(\pi/3)\cos(2\pi ft - \pi/3)$. The voltage difference between the input terminal and output terminal can be equivalent to an input voltage in input terminal, and output terminal is connected to the ground, as shown in Figure 9. We have mentioned above that diodes VD_2 and VD_5 are turned off all the time, so **c** phase has no current. The circuit characteristics of Figure 9 are the same as Figure 6. Circuit simulation software Pspice is utilized to verify the above conjectures. Set frequencies f as 50Hz, as 200Hz, and as 500Hz; the I-V curves of input voltage u_{ab} and input current i_a are shown in Figure 10. As seen in Figure 10, the hysteresis loops are pinched at origin and the areas of hysteresis loop gradually decrease with the increase of the frequency. The characteristics of the pinched hysteresis loop conform to the

Table 4: Conduction situations of six diodes.

Time interval	I	II	III	IV
Conducting diodes	VD_1, VD_2, VD_6	/	VD_3, VD_4, VD_5	/
Input voltage relation	$u_a > u_{C^+} > 0$	$u_{C^+} \geq u_a$ and $u_{C^+} \geq 0$	$u_a < u_{C^+} < 0$	$u_{C^+} \geq u_a$ and $u_{C^+} \geq 0$

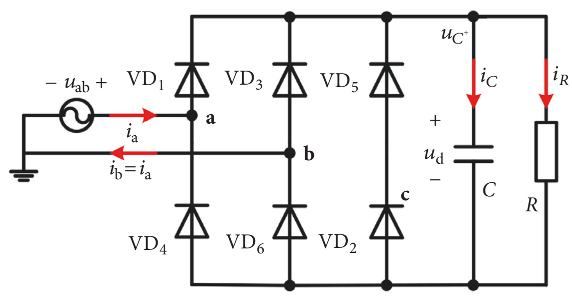

Figure 9: Equivalent circuit of three-phase bridge rectifier circuit running under single-phase short-circuit condition.

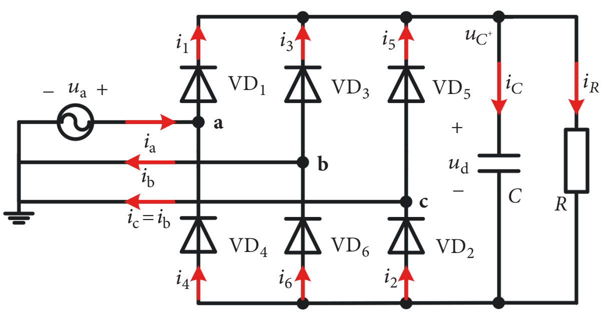

Figure 11: Three-phase bridge rectifier circuit running under two-phase short-circuit condition.

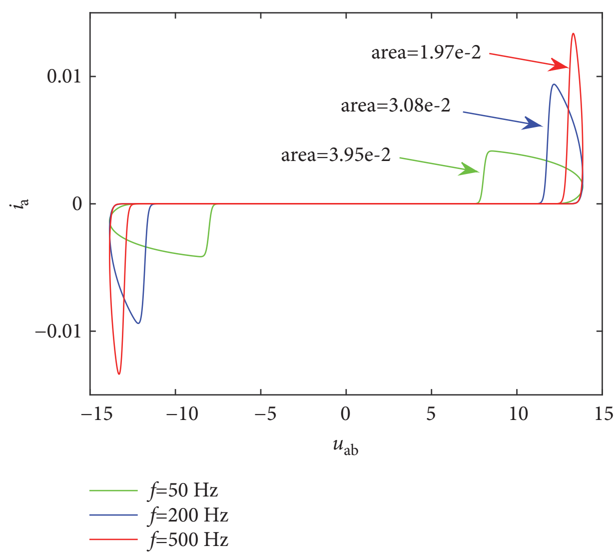

Figure 10: Curves of input voltage u_{ab} and input current i_a.

three fingerprints of the generalized memristor. Accordingly, when three-phase bridge rectifier circuit is running under the condition of **c** phase short-circuit, the circuit between **a** terminal and **b** terminal can be described as a generalized memristor.

2.3. Running under Two-Phase Short-Circuit Condition. When the three-phase bridge rectifier circuit is running under the condition of two-phase short-circuit, the circuit diagram can be seen as Figure 11, where **b** phase and **c** phase are short circuit to ground. Set the input voltage as $u_a = 8\sin(2\pi ft)$, $u_b = u_c = 0$, and make the same assumption that the conduction voltage of the diode is zero; the conduction situations of six diodes are shown in Table 4. Diodes VD_1, VD_2, and VD_6 are conductive when input voltage u_a is larger than the voltage at the positive terminal of the capacitor C, and the current flowing through the diode VD_2 is equal to that of diode VD_6 and equal to half of the current flowing through diode VD_1.

When input voltage u_a is less than the capacitor voltage u_{C^+} and $u_{C^+} \geq 0$, capacitor C discharges and diodes switch off. Conduction situations of diodes in time intervals III and IV are similar to those in time intervals I and II, respectively, where, in time interval III, the current flowing through the diode VD_3 is equal to that of diode VD_5 and equal to half of the current flowing through diode VD_4.

For the three-phase bridge rectifier circuit running under the condition of two-phase short-circuit, the current in **a** phase cannot be deduced simply from the single-phase diode bridge circuit because there is three-diode conduction at the same time. The current i_a can be written as follows applying Kirchhoff's current law:

$$i_a = i_1 - i_4 \tag{5}$$

By the same way, we can get

$$i_1 + i_3 + i_5 = i_C + i_R \tag{6}$$

And from above analysis we know that

$$i_4 = 2i_3 = 2i_5 \tag{7}$$

And

$$i_1 = 2i_2 = 2i_6 \tag{8}$$

From equations (5), (6), and (7), we get

$$2i_1 = i_a + i_C + i_R = i_a + C\frac{du_d}{dt} + \frac{u_d}{R} \tag{9}$$

In addition, the constitutive relations of diodes VD_k (k=1~6) can be described as

$$i_k = I_S\left(e^{2\rho u_k} - 1\right) \tag{10}$$

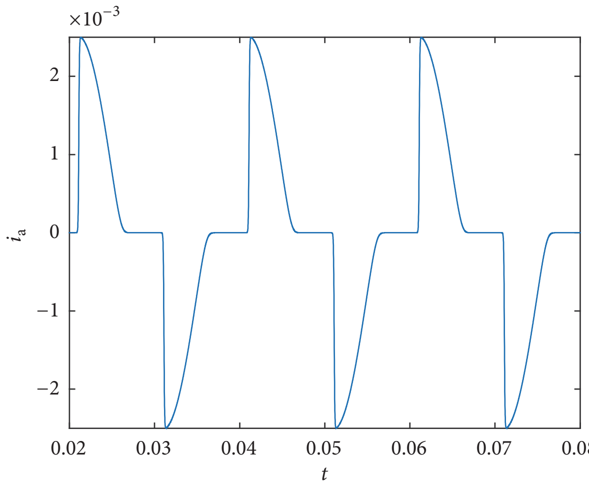

FIGURE 12: Input current of **a** phase versus time t.

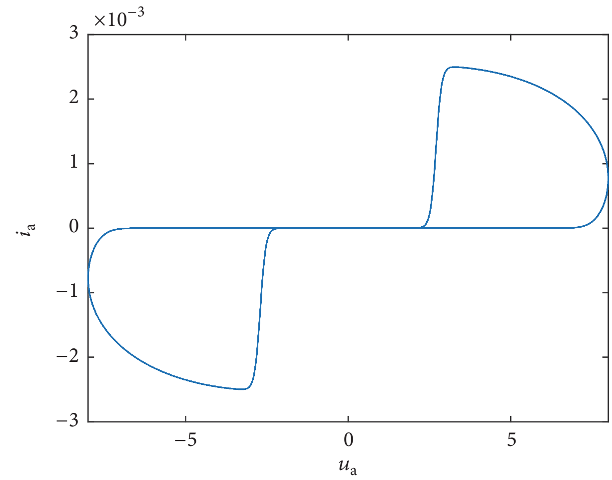

FIGURE 13: Locus in v-i plane.

where u_k represents the voltage across the corresponding diodes VD_k. Considering $u_3 = u_1 - u_a$ and substituting equations (7) and (10) into equation (5) yield

$$\begin{aligned} i_a &= I_S\left(e^{2\rho u_1}-1\right)-2I_S\left(e^{2\rho u_3}-1\right) \\ &= I_S e^{2\rho u_1}-2I_S e^{2\rho(u_1-u_a)}+I_S \\ &= I_S e^{2\rho u_1}\left(1-2e^{-2\rho u_a}\right)+I_S \end{aligned} \tag{11}$$

When the three-phase diode bridge rectifier circuit is running in time interval I, diodes VD_1, VD_2, and VD_6 break over; applying Kirchhoff's voltage law, we get

$$u_a = u_1 + u_d + u_2 \tag{12}$$

The relationship between u_1 and u_2 can be obtained by substituting equation (10) into equation (8), which can be described as

$$e^{2\rho u_1} = 2e^{2\rho u_2} - 1 \tag{13}$$

Thus, the mathematical model of **a** phase current when three-phase diode bridge rectifier circuit is running under two-phase short-circuit condition in time interval I can be calculated by equations (9)~(13). In the same way, we can obtain the mathematical model of **a** phase current when three-phase diode bridge rectifier circuit is running under two-phase short-circuit condition in time interval II, which can be computed by the following equations:

$$u_a = -u_4 - u_d - u_5 \tag{14}$$

$$i_a = I_S e^{2\rho u_4}\left(2e^{2\rho u_a}-1\right)-I_S \tag{15}$$

$$i_a + 2i_4 = C\frac{du_d}{dt} + \frac{u_d}{R} \tag{16}$$

$$e^{2\rho u_4} = 2e^{2\rho u_5} - 1 \tag{17}$$

$$i_4 = I_S\left(e^{2\rho u_4}-1\right) \tag{18}$$

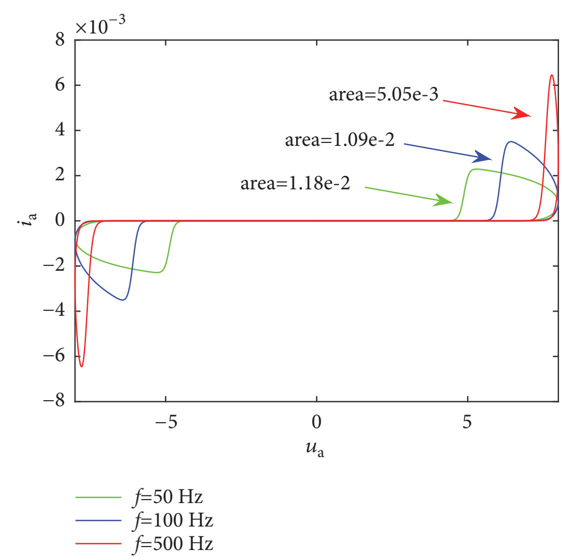

FIGURE 14: Curves of input voltage u_a and input current i_a.

Take the same parameters as in Table 2; numerical simulation can be carried out, and the current of **a** phase can be obtained by summing the i_a of the two time intervals. Figure 12 indicates the input current of **a** phase versus time t, and the locus in v-i plane is given in Figure 13.

Set $f = 50$ Hz, 100 Hz, and 500Hz; circuit simulation results show that the loci of **a** phase in the I-V plane are hysteresis loops and are pinched at the origin, as depicted in Figure 14. Same as the phenomenon like single-phase short-circuit, the area of the pinched hysteresis loop decreases as the frequency increases and the hysteresis loop shrinks to a nonlinear single-valued function when frequency increases to large enough. The I-V characteristic curves satisfy the substitutive characteristics of a memristive element and can be considered as a generalized memristor from **a** phase when two-phase short-circuit occurs in **b** phase and **c** phase.

2.4. Running under Interphase Short-Circuit Condition. Assuming the line impedance $R_a = R_b = R_c = 0.1\Omega$,

Table 5: Conduction situations of six diodes.

Time interval	I	II	III	IV
Conducting diodes	VD_1, VD_2, VD_6	/	VD_3, VD_4, VD_5	/
Input voltage relation	$u_a' > u_{C^+} > u_b' = u_c'$	$u_{C^+} \geq u_a, u_b, u_c$	$u_b' = u_c' > u_{C^+} > u_a'$	$u_{C^+} \geq u_a, u_b, u_c$

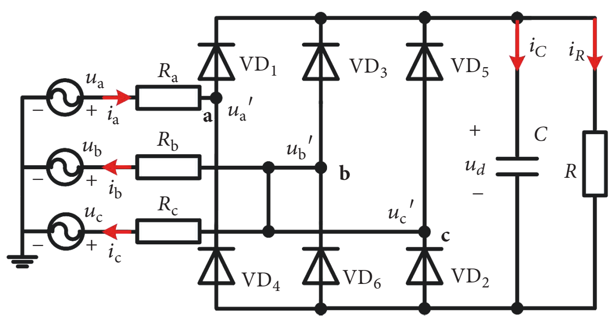

Figure 15: Three-phase bridge rectifier circuit running under interphase short-circuit condition.

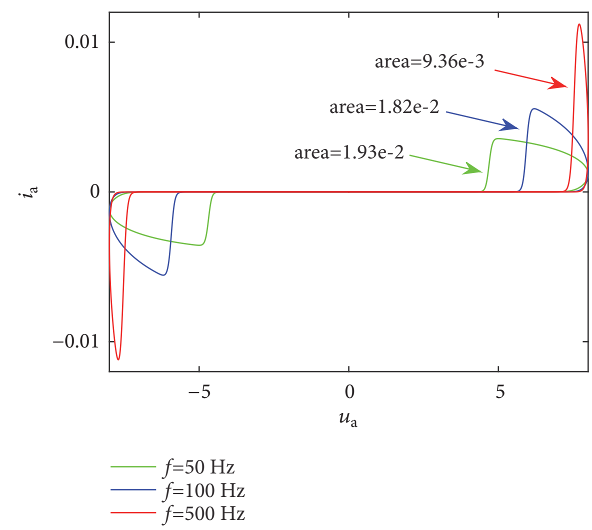

Figure 16: Curves of input voltage u_a and input current i_a.

the schematic diagram of three-phase bridge rectifier circuit running under interphase short-circuit condition is shown in Figure 15, where u_a, u_b, u_c and i_a, i_b, i_c are input voltages and input currents, respectively, and u_a', u_b', and u_c' are the positive voltages of diodes VD_1, VD_3, and VD_5. Set the three-phase input voltage as $u_a = 8\sin(2\pi ft)$, $u_b = 8\sin(2\pi ft - 2\pi/3)$, and $u_c = 8\sin(2\pi ft - 4\pi/3)$, and also suppose the conduction voltage of the diode is zero; the conduction situations of six diodes are shown in Table 5.

It can be seen that the voltage of **b** phase equals that of **c** phase because of the short circuit between **b** phase and **c** phase. As a result, diodes VD_2 and VD_6 switch on at the same time and share the current of diode VD_1. In the same way, diodes VD_3 and VD_5 share the current of diode VD_4 in time interval III. The mathematical model of **a** phase current is similar to that of **a** phase current when three-phase diode bridge rectifier circuit is running under two-phase short-circuit condition; the only difference is to change u_a in equations (11), (12), (14), and (15) into u_a'. In order to validate whether the input voltage and the input current of **a** phase accord with the pinched hysteresis loop, circuit simulation is carried out when the frequencies of the input voltage are set as 50 Hz, 200 Hz, and 500Hz, and the *I-V* characteristic curves are depicted in Figure 16.

It can be seen that areas of the loci in the *I-V* plane decrease as the frequency increases and finally reduce to zero, and the hysteresis loops are pinched at the origin. Samely, it can be named as a generalized memristor from **a** phase when interphase short circuit occurs between **b** phase and **c** phase.

2.5. Running under Single-Phase Open-Circuit Condition. The circuit structure of three-phase bridge rectifier circuit running under single-phase open-circuit condition is depicted in Figure 17. Due to the voltage drop of the resistor, the voltage of A terminal is always higher than that of B terminal; hence the diodes VD_2 and VD_5 are turned off all the time, the same situation as the three-phase bridge rectifier circuit running

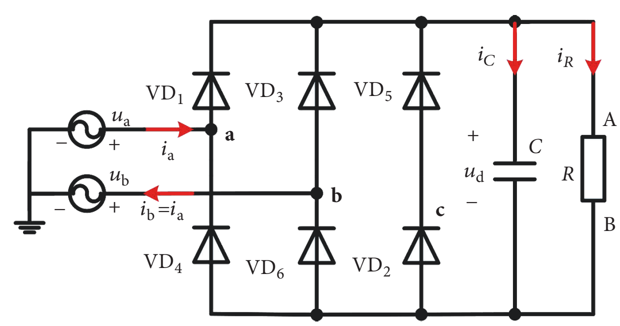

Figure 17: Three-phase bridge rectifier circuit running under single-phase open circuit condition.

under the single-phase short-circuit condition. Therefore, the mathematical model of **a** phase current is the same as equation (4). Set the same parameters as the condition under single-phase short-circuit; the *I-V* characteristic curves are the same as that of the three-phase bridge rectifier circuit during single-phase short-circuit, which is illustrated in Figure 10. As a result, the circuit between **a** terminal and **b** terminal can be described as a generalized memristor.

3. Conclusions

The analyses of whether a three-phase diode bridge rectifier circuit can be called as a generalized memristor are discussed in this paper. The discussion is carried out when three-phase bridge rectifier circuit is running under normal operation or single-phase short-circuit, two-phase short-circuit, interphase short-circuit, and single-phase open-circuit conditions. Assume that the tube voltage drop of diode is zero; the conduction situations of six diodes are investigated and circuit operation conditions are analyzed. The pinched hysteresis loops are numerically simulated in MATLAB and validated by circuit simulation software PSpice. The results confirm that the three-phase diode bridge rectifier circuit has memristive characteristics during several working conditions.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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