THE FIRST MAN-MADE MEMRISTOR: CIRCA 1801

Abstract | This article reexamines the historical carbon arc discharge experiment conducted by Humphry Davy in 1801. We present experimental evidence which indicates that such a carbon arc discharge is not only the first artificial light source, but also the world's first man-made memristor ever reported in the scientific literature. The original carbon arc discharge experiment has been repeated with modern power supply equipment with bipolar excitation capability. The carbon arc discharge exhibits the three fingerprints of memristors, including the pinched hysteresis loops, the lobe area changing with operating frequency, and such lobe area approaching zero as the operating frequency increases.

KEYWORDS | Carbon arc; discharge; memristor; modeling

The carbon arc lamp has been regarded as the earliest form of artificial electric light sources and is the cornerstone of artificial lighting technology.

I. INTRODUCTION

Based on the batteries invented in 1800 by the Italian scientist Alessandro Volta [1], Humphry Davy (1778–1829) of Cornwall, U.K., reported the famous carbon arc discharge experiment in 1801 [2] and demonstrated it at the Royal Institution as a carbon arc lamp [3]. His test report on generating light without using fire [2] was believed to be the first written record of artificial lighting. The carbon arc lamp has been regarded as the earliest form of artificial electric light sources and is the cornerstone of artificial lighting technology. Humphry Davy, a renowned Chemist and later President of the Royal Society (Fig. 1), was recognized for his many research achievements, including the discoveries of several alkali and alkaline earth metals and the elemental nature of chlorine and iodine [4]. His achievements were of such a high status that even during the state of war between England and France, Humphry Davy accompanied by his laboratory assistant Michael Faraday, traveled to Paris, France, to receive the Emperor's Medal from Napoleon in 1806 [5].

While the significance of the carbon arc discharge was well recognized in the community of lighting technology as the first artificial light source, there is a very important aspect of this scientific experiment that had not been recognized until a seminal paper in *Nature* [6] reported a man-made memristor by a group of scientists from Hewlett Packard (HP) in 2008. Memristor was first postulated by Leon Chua in 1971 as a missing nonlinear passive two-terminal electrical component relating electric charge and magnetic flux linkage [7]. The practical realization of the memristor by the HP researchers, after 37 years of Chua's discovery, has since triggered a new wave of research in memristors, not only in electric devices and circuits, but also in a wide range of scientific disciplines such as biological science [8–11] and botany [12].

Fig. 1. *Portrait of Humphry Davy by Thomas Phillips.*

We have reexamined the carbon arc discharge experiment originally conducted at atmospheric pressure without any enclosure filled with special gases and metals (used in modern discharge lamps) by Humphry Davy and repeated it with modern power supply with bipolar excitation capability required to confirm that carbon arc discharge exhibits the three fingerprints of a memristor [9], [13]:

1) the Lissajous curve in the voltage–current plane is a pinched hysteresis loop when driven by any bipolar periodic voltage or current with zero mean for any initial conditions;
2) beyond a certain threshold frequency, the area of each lobe of the pinched hysteresis loop shrinks as the frequency of the forcing signal increases;

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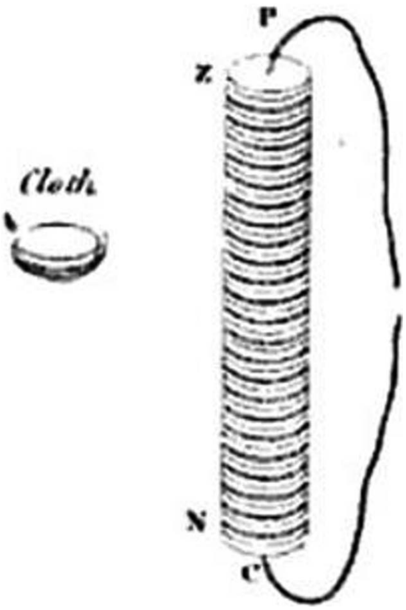

Fig. 2. *DC battery comprising a stack of zinc and silver discs, with zinc–silver cells separated by cloth moistened with "a compound of sulphur of potassa" [15].*

3) as the frequency tends to infinity, the hysteresis loop degenerates to a straight line or a single-valued curve through the origin, whose slope depends on the amplitude and shape of the forcing signal [13].

II. CARBON DISCHARGE DRIVING CIRCUIT AND EXPERIMENTAL SETUP

A1. Original Setup Driven by a DC Voltage Source

Humphey Davy was curious of the direct current (dc) batteries developed by Alessandro Volta and the Galvanic experiments. He set up battery systems to conduct tests which are now called electrolysis [2]. DC batteries were set up by stacking up many cells of zinc and silver plates or zinc and copper plates. Fig. 2 shows one example in which cloth moistened with "sulphret of potassa" was used to separate individual cells. An alternative approach to develop large dc battery was to immerse a group of large zinc and copper plates into a container of chemical solution such as acidic or alkaline solutions (Fig. 3).

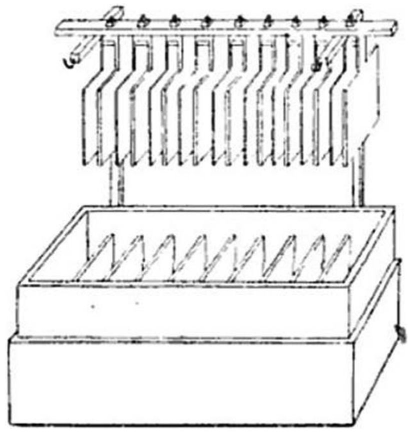

Fig. 3. *Construction of dc battery by immersing series-connected zinc and copper plates in a container of chemical solution [15].*

Referring to the charcoal rods (being used as the electrodes in the Galvanic experiments), Humphrey Davy wrote that "I have found that this substance possesses the same properties as metallic bodies in producing the shock and spark, when made a medium of communication between the ends of the galvanic pile of Signor Volta" [14], pp. 150–151. Such spark was the arc discharge (Fig. 4) between the tips of the carbon rods. Based on this principle, Humphrey Davy used a large battery bank to generate a continuous dc arc discharge in the electric light experiment at the Royal Institution in 1813 (Fig. 5).

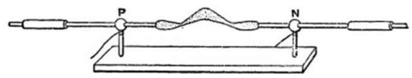

Fig. 4. *Drawing of the carbon arc discharge in Davy's work [15].*

A2. Modern Setup Driven by AC Voltage Source

The schematic of our carbon rod discharge driving circuit is shown in Fig. 6. Two carbon rods with 4-mm diameter are used as electrodes. A bipolar power supply is used to generate sinusoidal voltage of about 28-V root mean square (rms; from +40 to −40 V peak to peak) at frequency from 5 to 12 kHz. The current capacity is 14-A rms (from +20 to −20 A peak to peak). Eight air-cored inductors of 130 μH each are connected in various combinations of series and parallel connections in order to form a

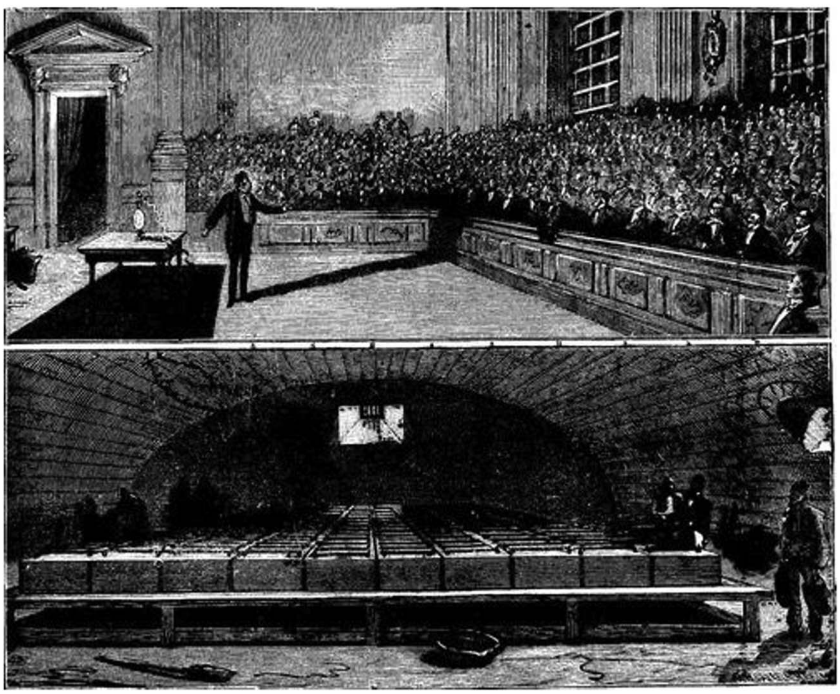

Fig. 5. *Picture of Humphrey Davy demonstrating the electric light for the members of the Royal Institution in London in 1813 and a picture of the large battery bank [16].*

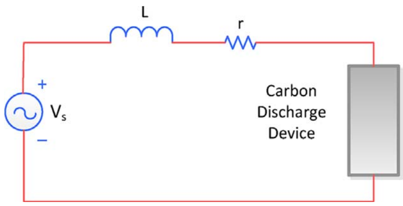

Fig. 6. *Schematic of carbon discharge driving circuit.*

variable inductor with inductance ranging from 16.25 μH to 1.04 mH. This air-cored inductor is used as a current limiter.

Following Davy's original experiment, our carbon arc discharge experiments are conducted with the discharge current flowing across the air gap without any glass enclosure of special gases and metal vapor. A photograph of the setup with the carbon arc discharge in operation is included in Fig. 7. The glowing arc current generates light as expected.

III. EXPERIMENTAL EVALUATION

The carbon arc discharge has been tested for a range of operating frequencies from 5 Hz to 12 kHz. For each operating frequency, the test is conducted according to the following procedures.

1) With the two carbon rods touching each other initially, adjust the air-cored inductance and activate the power supply to make sure that the short-circuited current is about 12-A rms at the tested frequency and maximum voltage output.
2) Then, separate the two electrodes slightly to ignite the arc.

Fig. 7. *Photograph of a carbon arc discharge in operation.*

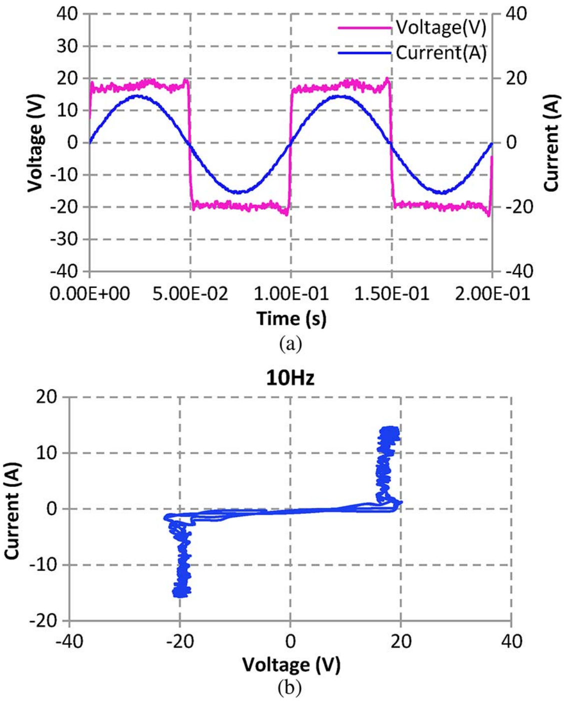

Fig. 8. *(a) Experimental voltage and current waveforms. (b) V–I hysteresis loop of carbon rod discharge at 10 Hz.*

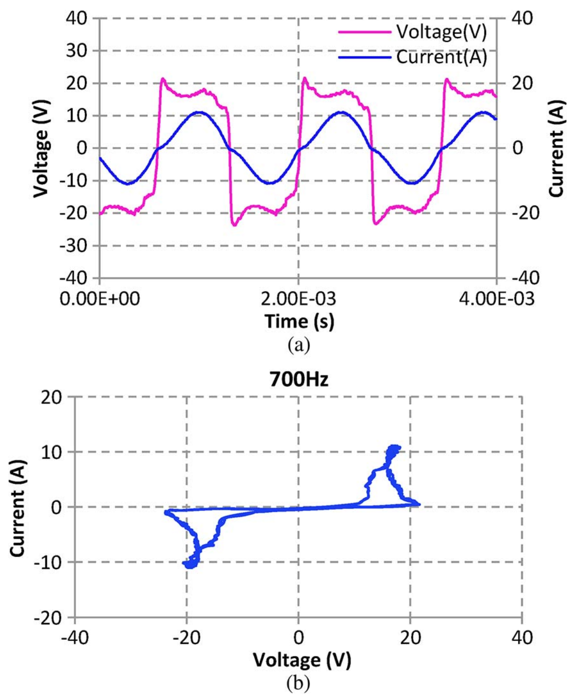

Fig. 9. *(a) Experimental voltage and current waveforms. (b) V–I hysteresis loop of carbon rod discharge at 700 Hz.*

When the arc discharge becomes stable, record the waveforms of voltage across the arc and current flowing through the arc.

It should be noted that as the arc burns, the tips of the carbon rods will be burnt off gradually, resulting in an increasing air gap. The arc will burn until the arc length and its associated arc resistance become too large for the electrode voltage to sustain the arc discharge current. Therefore, in the tests, the arc voltage and current waveforms are captured quickly for a range of frequencies with the understanding that the air gaps for different measurements are close to one another but are not exactly identical. However, it will be shown that these waveforms, despite being recorded at slightly difference air gaps, still exhibit the three fingerprints of memristors.

The measured Lissajous plots recorded at 10 Hz, 700 Hz, 3 kHz, and 12 kHz are shown in Figs. 8–11 in ascending frequency order. It can be seen that in all voltage and current waveforms, they cross over at the zero crossing points simultaneously. It is important to note that the arc voltage waveforms are close to a rectangular shape while the current waveforms are close to a sinusoidal shape unless the operating frequency exceeds tens of kilohertz.

From the V–I loci from Figs. 8(b)–11(b), three important observations can be made.

1) Pinched hysteresis loops can be observed in all sets of experimental measurements. This feature confirms the first fingerprint of a memristor.
2) The lobe area of the pinched hysteresis loops is frequency dependent. It is close to zero at low frequency such as 10 Hz. It increases in the range from 100 to about 700 Hz, and then decreases with increasing frequency. This is the second fingerprint of a memristor.
3) At high-frequency operation such as 12 kHz, the lobe area becomes close to zero. This is the third fingerprint of a memristor.

The measured lobe area of the carbon arc discharge over a range of frequency is plotted in Fig. 12. The threshold frequency where the lobe area decreases monotonically toward zero is about 800 Hz.

Davy's carbon arc discharge can now be fitted into a general

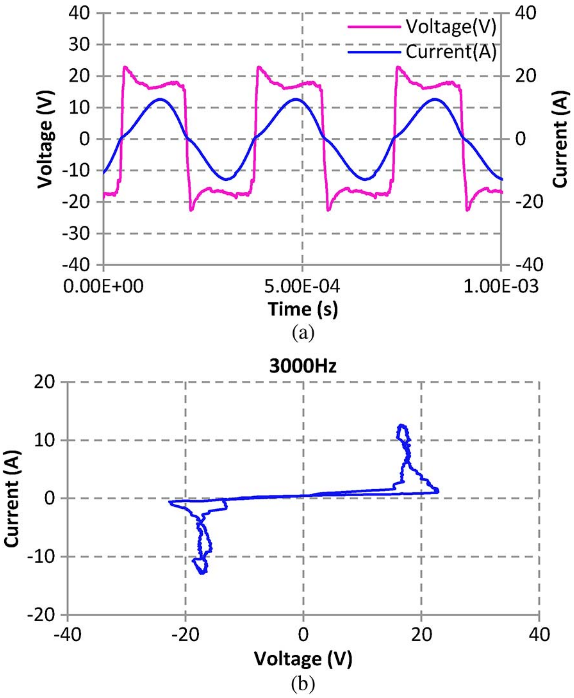

Fig. 10. *(a) Experimental voltage and current waveforms. (b) V–I hysteresis loop of carbon rod discharge at 3000 Hz.*

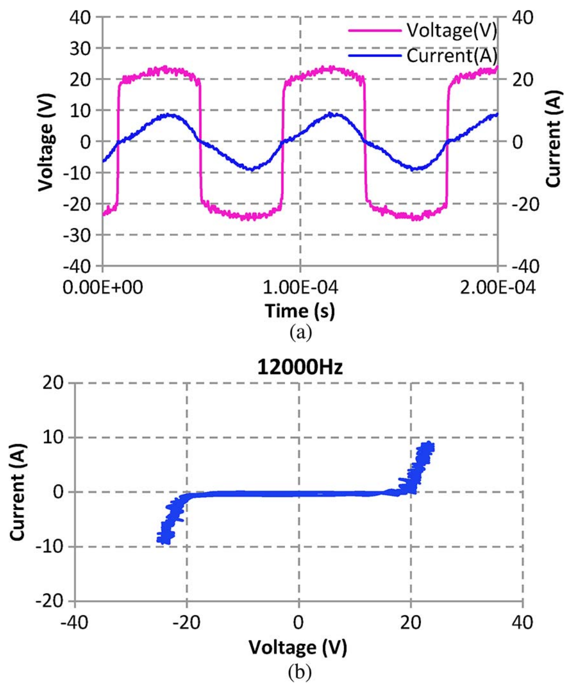

Fig. 11. *(a) Experimental voltage and current waveforms. (b) V–I hysteresis loop of carbon rod discharge at 12000 Hz.*

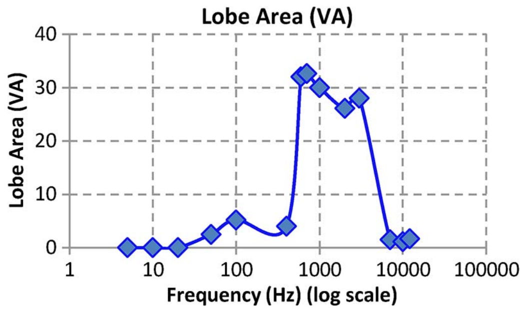

Fig. 12. *V–I lobe area for carbon rod discharge over a wide frequency range.*

mathematical framework for modeling discharge lamps as memristors [17]. The model is based on a set of physical equations as follows:

$$\frac{dT_e}{dt} = a_1(i^2R - P_{\mathrm{rad}} - P_{\mathrm{con}}) \quad (1)$$

$$P_{\mathrm{rad}} = a_2 \exp(-ea_3/kT_e) \quad (2)$$

$$P_{\mathrm{con}} = a_4(T_e - T_0) \quad (3)$$

$$R = a_5 T_e^{-3/4} \exp\left(\frac{ea_6}{2kT_e}\right) \quad (4)$$

$$V(t) = a_7 L \frac{di}{dt} + i(R + r) + v_{\mathrm{ele}} \quad (5)$$

where T_e is the electron temperature; i is the arc current; R is the arc resistance; P_{rad} is the radiative power loss; P_{con} is the conductive power loss; T_o is the ambient temperature; $V(t)$ is the applied ac voltage; L is the current limiting inductance; r is the winding resistance of the inductor; v_{ele} is the electrode voltage drop; and a_1–a_7 are model coefficients for the arc discharge.

The generalized discharge lamp model equations can be used to check their three fingerprints of memristor. The relationship between the discharge arc voltage and current is

$$v(t) = R(T) \cdot i(t) \quad (6)$$

where R is a function of the temperature as follows:

$$R(T) = a_5 T^{-3/4} \exp\left(\frac{ea_6}{2kT}\right). \quad (7)$$

From (7), the scalar state variable x is T. Note that T is related to the current $i(t)$ through the following equation:

$$\begin{aligned}\frac{dT}{dt} &= f(T, i)\\ &= a_1\left[i(t)^2 R(T) - a_2 \exp(-ea_3/kT)\right.\\ &\qquad \left. - a_4 \exp(T - T_0)\right]. \end{aligned} \quad (8)$$

The discharge process is highly complex and nonlinear. Equations (6)–(8) are coupled nonlinear equations that can be solved numerically. Based on the information provided in Table 1, the theoretical arc voltage and current waveforms of Davy' carbon arc discharge can be derived. Fig. 13(a) shows the predicted pinched hysteresis loops of the carbon arc discharge at 400, 600, 1000, and 3000 Hz. The corresponding measured loops are displayed in Fig. 13(b). These results show that the theoretical memristor model can predict the carbon arc discharge behavior with good accuracy.

IV. CONCLUSION

The carbon arc discharge experiment conducted by Humphrey Davy has been considered as the first written record on artificial lighting. The Davy's carbon arc experiment has in fact more scientific implications than previously conceived. This article presented the experimental evidence to show that such a carbon arc discharge is not only the first artificial lighting

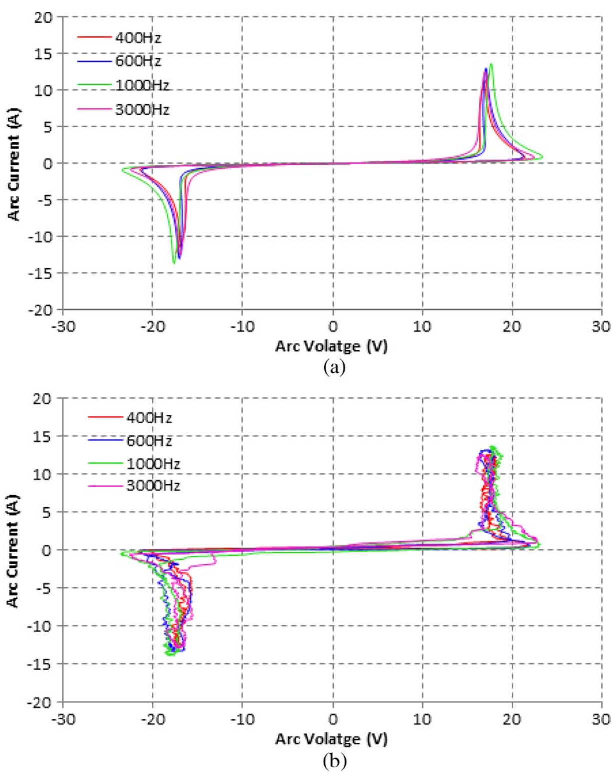

Fig. 13. *(a) Theoretical pinched hysteresis loops for the carbon arc discharge at 400, 600, 1000, and 3000 Hz. (b) Measured pinched hysteresis loops for the carbon arc discharge at 400, 600, 1000, and 3000 Hz.*

Table 1 Model Coefficients Used for the Theoretical Predictions for Fig. 13(a)

Freq.	a_1	a_2	a_3	a_4	a_5	a_6	a_7
400Hz	9.92x10^5	19.61 x10^6	3.86	0.07	428.05	0.19	1.34
600Hz	13.73 x10^5	12.83 x10^6	10.76	0.08	385.74	0.19	1.12
1kHz	19.40 x10^5	9.57 x10^6	12.75	0.08	418.82	0.19	1.25
3kHz	50.08 x10^5	4.44 x10^6	17.16	0.08	400.21	0.17	1.23

device, but also the first man-made volatile memristor [18].[1] All of the three fingerprints of a memristor can be observed in the carbon arc discharge experiments. It is also demonstrated that the carbon arc discharge behavior can be modeled by the general mathematical framework developed for a memristor. It is hoped that the practical evidence presented here will give the scientific community some new understanding on the historical significance of the carbon arc research of Humphry Davy.[2] ■

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[1]There are two types of memristors [18]. The memristor reported by HP in the *Nature* paper is a "nonvolatile" memristor. The vast majority of memristors, including the first man-made "Carbon-arc" memristor, are "volatile" memristors, which are found in many other two-terminal electrical devices, as well as nonelectrical two-terminal circuit element models, such as synapses, ion channels, axons, etc.

[2]Video clips of the dynamic carbon arc discharge and its pinched hysteresis loop can be watched at the following links: 1) https://www.youtube.com/watch?v=1kboMCaGuMw; and 2) https://www.youtube.com/watch?v=6mzzYiEWyDA

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