



Electrical modelling of dielectric barrier discharge cold plasma reactor powered by a photovoltaic conversion system

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ABSTRACT

The study develops a detailed MATLAB/Simulink electrical model to analyze the behavior of a Dielectric Barrier Discharge (DBD) plasma reactor. This reactor is energized by a Photovoltaic Conversion System (PVCS), which integrates a PV generator, a DC/DC boost converter, a single-phase DC/AC inverter, an LC filter, and an AC/AC autotransformer to achieve the required high-voltage, sinusoidal AC signal with adjustable voltage and frequency. The simulation outcomes not only quantify the injected power but also elucidate critical discharge parameters, such as the total, dielectric, and gas gap capacitances, alongside the positive and negative breakdown voltages and the peak operating voltage.

1. INTRODUCTION

Often called the fourth state of matter, plasma is a distinct phase achieved by adding energy to a gas. Continuing the progression from solid to liquid to gas, plasma represents matter in its most energetic state (Ichimaru, 2018). The very word "plasma" was coined in 1923 by Langmuir and Tonks (1929) to describe this high-energy state, a supercharged gas teeming with electrically charged particles like electrons and ions, alongside neutral atoms. What truly sets plasma apart is its ability to conduct electricity, something a regular gas simply cannot do. Moreover, despite sounding exotic, it is actually the most common state of matter in the universe accounting for an estimated 99% of everything we can see (Chen & Chang, 2003).

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The utility of plasma derives from its intrinsic capacity to conduct electricity and generate reactive species. This property is exploited in manufacturing for surface activation, cleaning, and functionalization to facilitate coating or printing processes. In urban environments, plasma-generated ozone is employed for water purification, and plasma-based systems are used for air remediation. Within the medical field, plasma is an area of intense research, with potential applications encompassing equipment sterilization, wound therapy, and oncology (O'Neill et al., 2024). Industrially, it is instrumental in the synthesis of advanced materials, including novel polymers and nanoparticles (Jung et al., 2025). Furthermore, plasma technology is emerging as a potential cornerstone of a sustainable energy future, with researchers leveraging it for the production of clean H₂ as part of the transition away from fossil fuels (Srinivasan et al., 2026).

One particularly important technology for plasma generation, especially under high-pressure conditions, is the Dielectric Barrier Discharge (DBD). For decades, this technique has been recognized for its ability to generate cold, non-equilibrium plasmas while reliably avoiding the formation of thermal arcs (Subedi et al., 2017). The defining characteristic of a DBD reactor is the strategic placement of at least one insulating dielectric layer between the gas and the electrodes. These reactors can be designed in two main configurations: closed systems, like plasma lamps with permanently sealed gas, or open systems, such as those used for continuous exhaust gas treatment (e.g., NO_x removal) (Abdel-Naeem et al., 2022).

Historically, the primary industrial application of DBDs was ozone production. The fundamental principle involves an electrical discharge forming between electrodes, where a dielectric material covers at least one of them. This dielectric plays two essential roles. On one hand, it inherently restricts the charge released during a single discharge event, thereby controlling the average current density. On the other hand, it encourages the distribution of the discharge across the electrode surface as a multitude of micro-discharges, preventing the formation of a concentrated and potentially destructive arc (Adesina et al., 2024; Brandenburg et al., 2023; Lemos et al., 2026; Sulemana et al., 2025). A key operational consequence of the dielectric is the necessity to use alternating voltage sources.

In recent years, significant progress has been made in both the experimental applications and the electrical modeling of dielectric barrier discharges (DBDs). This progress reflects a broader scientific trend fueled by the increasing accessibility of high-performance computing. These computational capabilities now enable researchers to develop and solve complex models and conduct highly detailed simulations that were once impractical. As a result, scientists have gained unprecedented insight into the fundamental physics governing these discharges (Wang et al., 2025; Iposi, 2025; Chenoui et al., 2026). The growing accuracy of these simulation-based predictions has, in turn, encouraged more researchers to adopt modeling as an essential tool for analyzing discharges and plasma processes.

Within the specific context of DBDs, modeling efforts typically aim to improve the understanding of key phenomena, including chemical kinetics, charged particle dynamics, electrical energy deposition in the gas, and the transport of individual species. In some cases, modeling may also seek to create predictive tools capable of simulating plasma devices in a comprehensive manner. Electrical models, in particular, represent a well-established research approach whose value and benefits are widely acknowledged. They serve as a powerful complement to experimental methods, enabling broader or more detailed investigations while offering far greater flexibility in application.

One practical approach involves modeling DBDs using an equivalent electrical circuit. This method simplifies the study of interactions between a DBD reactor and its electrical generator. For instance, it facilitates the precise analysis of electrical waveforms associated with the reactor, the calculation of electrical energy injected into the gas, and the appropriate sizing of generator components such as transformers and semiconductor switches. Moreover, this modeling approach provides access to

electrical parameters that are difficult to measure directly through experiments such as the voltage across the gas and dielectrics, or the conduction current flowing through the gas during plasma ignition.

Numerous studies have proposed electrical models for dielectric barrier discharges (DBDs) to address objectives ranging from system sizing and energy characterization to the elucidation of physical phenomena, optimization, diagnosis, and process control. An electrical model validated against experimental measurements demonstrated that the surface resistivity of the dielectric material constitutes a critical parameter governing discharge behavior (Tay et al., 2014). A physics-based model developed by Wilde et al. (2017) accurately predicted power consumption in surface DBDs for aerospace applications. Following extensive validation against empirical data, the model reliably captures the influence of design parameters, thereby enabling enhanced optimization for flow control and propulsion systems. López-Fernandez et al. (2017) introduced an electrical equivalent circuit for a DBD cell capable of simulating both homogeneous and filamentary discharge modes. The model employs a controlled current source to represent the homogeneous regime and a switched RC network to replicate filamentary microdischarges. It provides accurate estimates of internal parameters and effectively distinguishes between discharge modes, demonstrating strong correlation with experimental observations. A plasma actuator utilizing dielectric barrier discharge was investigated (Orlov, 2006). In which, an optical emission measurements facilitated analysis of plasma dynamics under varying electrical conditions, and models were developed to quantify the electro-hydrodynamic force exerted on the surrounding air. Simulations confirmed the accuracy of these force predictions against experimental data. When integrated onto an airfoil, the actuator suppressed boundary layer separation and extended stall margins at elevated angles of attack, consistent with empirical observations. The study presented by Pal et al. (2010) employed DBDs with insulating layers to inhibit arc formation and generate non-thermal plasma, offering a mercury-free alternative for VUV/UV light sources. Experiments conducted with Xe/Ar gas mixtures revealed filamentary discharge behavior in argon-rich environments and homogeneous discharge in xenon-rich environments, findings that were corroborated through electrical modeling. Pal et al. (2009) investigated an argon-filled coaxial DBD reactor. An electrical model derived from the reactor's geometry and material properties was developed, and the application of high-frequency excitation produced filamentary microdischarges, confirmed through both optical and electrical diagnostics. The model's strong agreement with experimental data enabled precise determination of key electrical parameters, including impedance and power dissipation. Tyl et al. (2021) introduced a segmented electrode configuration for two-dimensional spatial mapping of dielectric barrier discharges. This diagnostic approach revealed that discharges perceived as macroscopically uniform exhibit significant spatial heterogeneity induced by factors such as gas flow, thereby advancing the fundamental understanding of spatiotemporal discharge dynamics.

This work presents an electrical modeling and simulation of a DBD plasma reactor energized by a PVC. The primary goal is to analyze the behavior and characteristics of the reactor as a function of different electrical model parameters, while also considering the influence of the power supply conditions. The key contributions of this research are summarized below:

1. A detailed modeling and simulation of a coaxial cylindrical DBD reactor is carried out under diverse operating conditions, highlighting the impact of parametric variations within the electrical model. The dynamic behavior of the discharge is characterized through its electrical signatures, and the charge transfer is evaluated using Lissajous figures obtained for various electrical parameters of the system.
2. The design of an AC power source with adjustable voltage and frequency are presented to enable the electrical characterization of the DBD reactor. This power supply system integrates a PV

array, a DC/DC Boost converter, a frequency-controlled single-phase inverter, an LC filter, and a voltage autotransformer.

2. SYSTEM DESCRIPTION

2.1 DBD Power sply circuit

A sinusoidal voltage is applied to a dielectric barrier discharge (DBD) reactor by the generator employed in this study. By modulating two key parameters, the amplitude and frequency (f) of the voltage (V) pulses, the generator provides precise control over the injected power. This dual-adjustment capability is a defining feature of the system, facilitating a parametric investigation into how different voltage waveforms influence treatment efficiency. The generator's architecture is divided into four primary subsystems, as illustrated in Fig. 1:

- A PV generator coupled with a boost converter. This unit, regulated by an incremental conductance INC-MPPT algorithm, functions as the DC source.
- A single-phase voltage inverter equipped with an LC filter.
- An AC/AC voltage autotransformer, which adjusts the voltage level.
- A single-phase inverter with their control module dedicated to managing both the f and V .

Within this configuration, the magnitude of the voltage pulses is governed by the DC source, whereas the inverter dictates their timing and f and the autotransformer adjusts the V level.

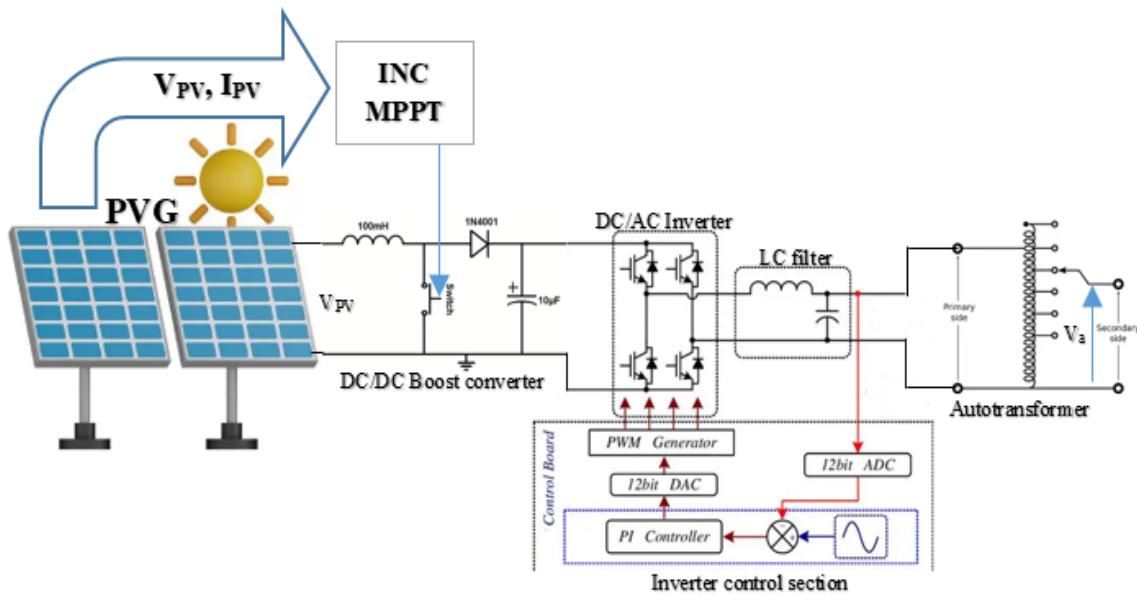


Fig 1. DBD Power supply circuit

2.2 DBD reactor circuit model

The foundation of this study is the electrical model of a cylindrical DBD reactor proposed by Pathak et al. (2025). In their work, the authors introduced an equivalent circuit composed of lumped elements that capture the electrical behavior of the DBD discharge system, accounting for the discharge gap, the dielectric layer, and the plasma impedance.

A state-dependent equivalent circuit model captures the operation of the DBD. In its non-conducting, or OFF, state, the DBD behaves as a purely capacitive load. This is accurately modelled as two capacitors in series: the dielectric barrier capacitance C_d and the gas gap capacitance C_g . The DBD switches to its conducting, or ON, state once the applied voltage V_a surpasses the critical breakdown threshold V_{bd} . At this point, the model assumes that current is conducted via a network of ignited micro-discharges that are uniformly distributed across the electrode surface. Thus, the DBD functions as a simple ON/OFF system, where the state is determined solely by whether V_a is below or above V_{bd} . Eq. 3 gives the combined capacitance of the series elements C_d and C_g , denoted as the total capacitance C_T .

$$C_d = \frac{2\pi\epsilon_0\epsilon_{r2}l}{\ln((d+x)/d)} \quad (1)$$

$$C_g = \frac{2\pi\epsilon_0\epsilon_{r1}l}{\ln((d)/r_0)} \quad (2)$$

$$C_T = \frac{C_g * C_d}{C_g + C_d} \quad (3)$$

where, ϵ_0 is permittivity of vacuum, ϵ_{r1} is the relative permittivity of gas flowing through the gap. ϵ_{r2} is the relative permittivity of the dielectric barrier, d is the internal radius of the dielectric. x is the thickness of the dielectric. r_0 is the inner electrode radius; l is the length of the outer electrode.

3. SIMULATIONS

The operational parameters for the simulation are defined in Table 1. The primary function of the power generation system is to deliver a controlled high voltage, denoted $V_a(t)$, to the DBD reactor, with an adjustable range of 0V to 12,000V. This is achieved through a multi-stage process: the PVG supplies a baseline 220V DC, which is subsequently stepped up to 1000V by a Boost converter and inverted to AC. The final voltage amplitude is precisely regulated by an autotransformer, whose taps (N1 through N6) allow for a continuous adjustment between 1000V and 12,000V. Concurrently, the frequency of the applied voltage is governed by the inverter's control system. The central aim of this research is to characterize the DBD reactor's electrical behavior. To this end, a numerical model was employed to simulate the reactor under various applied voltage conditions, enabling the calculation of its electrical characteristics and a quantitative assessment of its power consumption.

Fig. 2 illustrates the ignition and extinction conditions. With a sinusoidal applied voltage $V_a(t)$ supplied to the DBD reactor generated by the PVG system under 1000W/m^2 , 25C^0 , and an N1–N6 autotransformer breakdown occurs at times $t1$ and $t3$ corresponding to $V_a(t) = 0\text{V}$ and $V_a(t) = \pm V_{a\text{max}}$ respectively. Although the breakdown voltage V_a is not directly measurable, it can be estimated from the onset of micro discharges and the known peak voltage. The instants $t2$ and $t4$ are identified from Fig. 3 when $V_a(t) = \pm V_{a\text{max}}$. Fig. 3 shows the Lissajous figures for increasing applied voltage levels from $V_a(N1)$ to $V_a(N6)$. All figures share the same axis orientation in the Q(V) plane, indicating consistent discharge behavior. Fig. 4 presents the Lissajous figures at a constant $V_a = 12000\text{V}$ for frequencies from 50Hz to 300Hz. The area of the parallelogram, representing energy dissipation per cycle, is larger at lower frequencies and smaller at higher frequencies.

Table 1. Simulation system parameters

System	Variable	Value/Unit
PV generator	V_{OC}	21.7/V
	V_{mp}	19.8/V
	I_{SC}	5/A
	I_{mp}	3.28/A
	N_P	2/-
	N_S	12/-
Boost converter	V_{DC}	220→1000/V
	L_B	100/mH
	C_B	10/ η F
DC/AC inverter	IGBTs	-
LC filter	L	0.3/mH
	C	100/ η F
Autotransformer	N	-
	$N_1, N_2, N_3,$	-
	N_4, N_5, N_6	-
DBD reactor	$C_d,$	Eq. (1)/ η F
	$C_g,$	Eq. (2)/ η F
	C_T	Eq. (3)/ η F

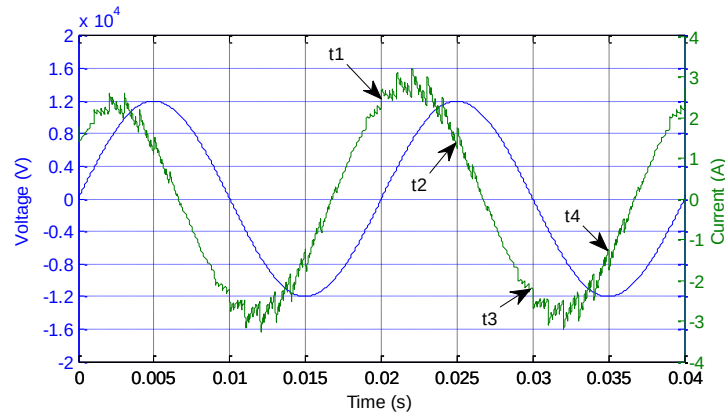


Fig 2. Waveforms of the DBD voltage $V_a(t)$ and the total current $i_T(t)$

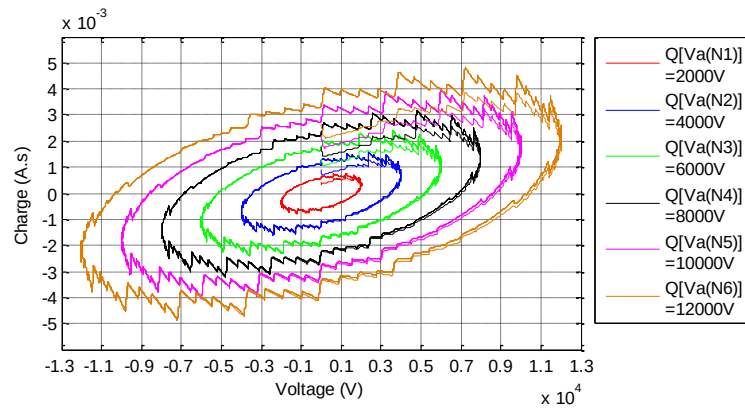


Fig 3. Q-V plots simulation when $V_a(t)=V_a(N1-N6)$ with $f=50\text{Hz}$

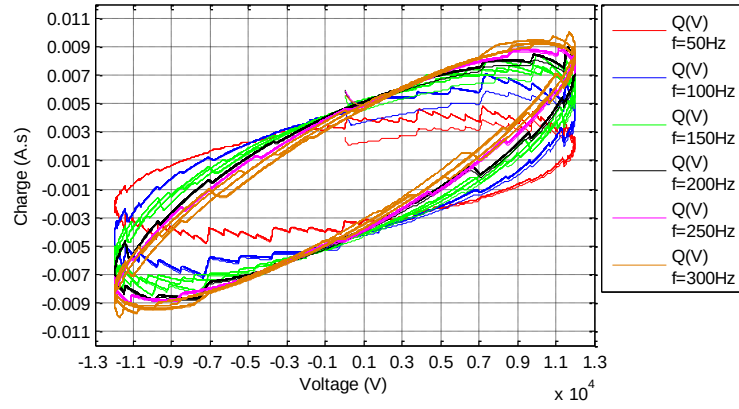


Fig 4. Q-V plots simulation when $f = (50\text{Hz}-100\text{Hz}-150\text{Hz}-200\text{Hz}-250\text{Hz}-300\text{Hz})$ with $V_a=12000\text{V}$

The charge Lissajous characteristics are depicted in Figs (5) and (6) for variations in C_d and C_g , respectively. As shown in Fig. 5, a decrease in C_d leads to a reduced charge and an improved Lissajous characteristic. Conversely, Fig. 6 demonstrates that modifications to C_g have a negligible impact on the charge characteristic. The influence of R_f on the Lissajous characteristic is illustrated in Fig. 7, where an increase in the charge is observed with higher values of R_f .

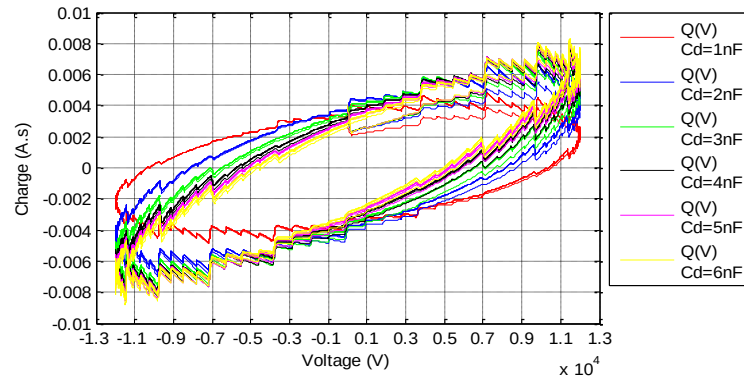


Fig 5. Q-V plots simulation when $C_d = (1\text{nF}-2\text{nF}-3\text{nF}-4\text{nF}-5\text{nF}-6\text{nF})$ with $V_a=12000\text{V}$ and $f=50\text{Hz}$

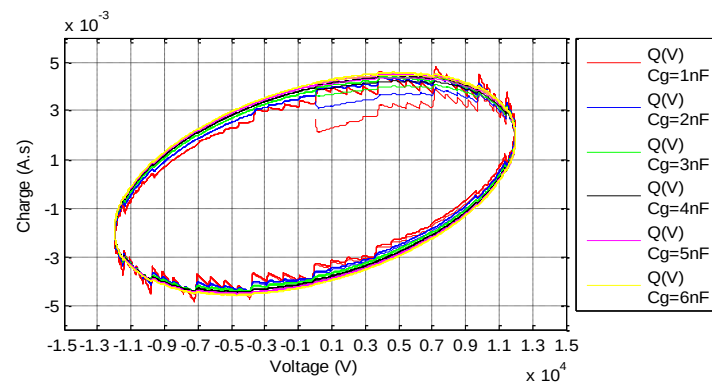


Fig 6. Q-V plots simulation when $C_g = (1\text{nF}-2\text{nF}-3\text{nF}-4\text{nF}-5\text{nF}-6\text{nF})$ with $V_a=12000\text{V}$ and $f=50\text{Hz}$

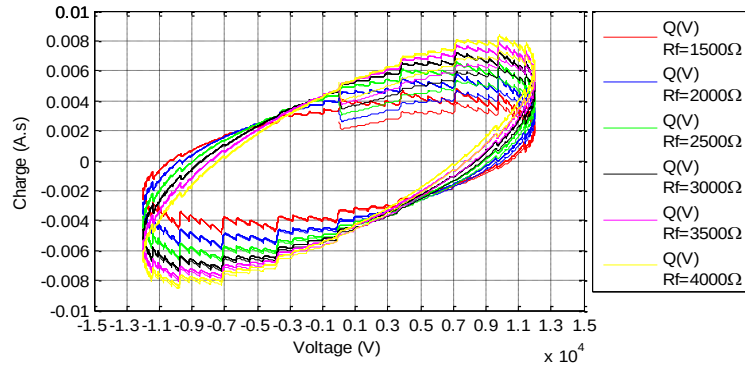


Fig 7. Q-V plots simulation when $R_f = (1500\Omega - 2000\Omega - 2500\Omega - 3000\Omega - 3500\Omega - 4000\Omega)$ with $C_d = 1\mu F$, $C_g = 1\mu F$, $V_a = 12000V$ and $f = 50Hz$

The discharge power, calculated as the product of the discharge current and the gap voltage, indicates the amount of power transferred to the reactor. As shown in Fig. 8, the discharge power increases with applied voltage but decreases with increasing frequency.

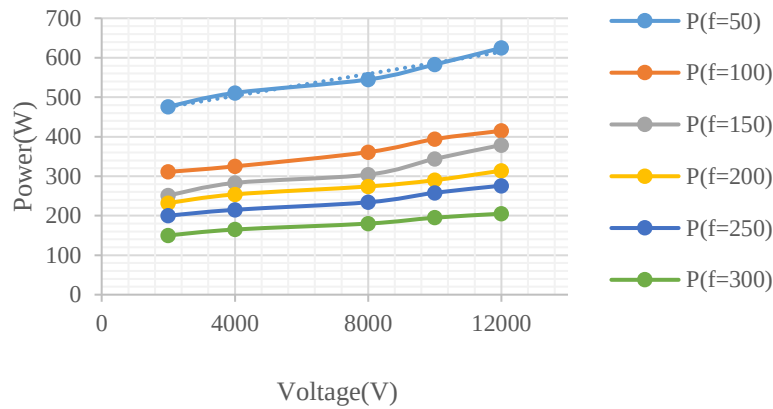


Fig 8. Average power consumption vs frequency changing

4. CONCLUSION

This paper presents an electrical model for a coaxial cylindrical DBD plasma reactor, powered by a PVC system. The proposed equivalent circuit is applicable to both the filamentary and homogeneous discharge regimes. The discharge dynamics are characterized using current-voltage characteristics, which align well with findings from the homogeneous regime. Charge transfer was quantified via Lissajous figures under various operating conditions, specifically by modulating parameters C_g , C_d , R_f , f , and V . The strong correlation between our simulation results and experimental data from the existing literature provides valuable insight into the underlying physics of DBD behavior.

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