Review of Power Systems of Non-Thermal Plasma Reactors and Their Applications

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Atmospheric pressure cold plasma has recently attracted considerable scientific interest and found a range of practical applications. Common sources of such plasma include dielectric barrier discharge (DBD), atmospheric pressure plasma jets (APPJ), and gas arc discharge (GAD). Various nonlinear phenomena occurring within the power supply–plasma reactor system – such as harmonic generation, resonance and ferroresonance, switching overvoltages, and pulse formation – can, when properly managed, enhance reactor performance. These effects contribute to more reliable plasma ignition, increased process efficiency, and improved integration of the plasma system with the electrical grid. The examples of power supplies used in plasma processes in power generation, environmental engineering, agriculture and medicine presented in this review confirm the above statement.

Keywords:
non-thermal plasma (NTP),
DB,
GA and APPJ rectors,
power systems of NTP reactors,
non-linear phenomena in plasma generation systems

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I Introduction

Non-thermal plasma (NTP), produced through electrical discharge, is being increasingly applied across a range of interdisciplinary fields, including energy, environmental protection, agriculture, and medicine. Plasma reactors (PRs) designed to generate atmospheric pressure cold plasma (APCP) are nonlinear energy consumers that utilize various types of electrical discharges. Depending on the specific application, their power requirements can range from several hundred watts – as seen in medical and agricultural contexts – to several tens of kilowatts in energy and environmental engineering. The power of the discharge, which reflects the reactor’s performance, is regulated by adjusting voltage, current, and/or frequency, depending on the discharge type.

An overview of power supply systems (PSS) for APCPs includes dielectric barrier (DB) reactors, which can be found in both classic DBD reactors and APPJ reactors, as well as two-electrode and multi-electrode GAD reactors, the latter of which can also be used as a two-electrode APPJ reactor. This selection is motivated by several factors: these types of electrical discharge are effective in generating NTP and the range of their potential applications is growing [1,2].

II Plasma reactors as electrical energy receivers

A. Plasma reactor with DBD

The DBD PR represents the capacitive-resistive receiver for the PSS. Structure of the discharge element of the DBD reactor is presented in Fig. 1(a) together with equivalent diagram (Fig. 1b), in which the non-linear conductivity G of the gas gap models the discharge after its ignition. When the applied voltage reaches the breakdown threshold, gas ionization takes place, and the discharge gap ceases to act as an insulator. Instantaneous values of supply voltage u(t), gap discharge voltage $u_g(t)$ and discharge current $i_G(t)$, presented in Figs.1(c) and 1(d), respectively.

The efficiency of a DBD reactor can be enhanced by raising the supply voltage frequency. However, this must be balanced against the associated rise in gas temperature within the discharge gap, which typically hinders the formation of particles and reactive species in plasma processes and necessitates the implementation of dedicated electrode cooling systems.

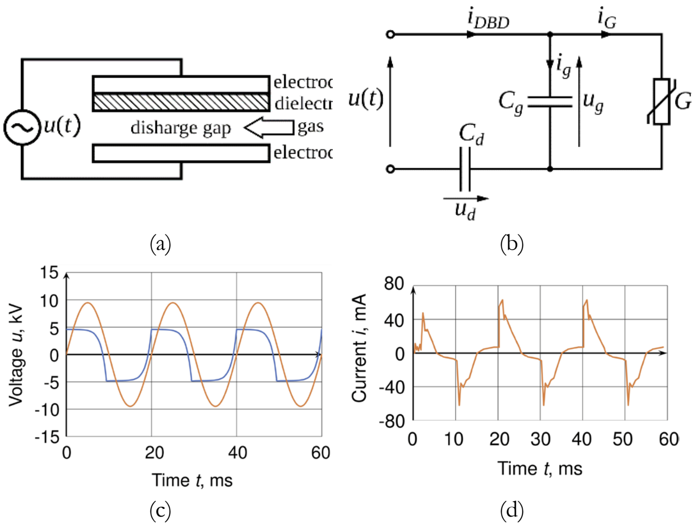

Figure 1: [2]: Structure of the DBD reactor (a); equivalent electrical diagram (b); numerical PSpice modelling results: supply voltage and gap voltage, (c), and discharge gap current (d), where: C_d – dielectric capacitance, C_g – discharge gap capacitance, G – non-linear conductance of the DBD, $u(t)$ – power source voltage, i_{DBD}, i_g and i_G – currents of the DBD PR, gap and non-linear conductance, respectively.

The discharge power and energy efficiency of plasma generation in a DBD system are influenced by several factors, including the geometry of the discharge components, the physical and chemical properties of the input gas, and key electrical parameters of the PSS – such as voltage amplitude, waveform, frequency, internal impedance of the power source.

The PSS of DBD PR has the character of a real voltage source, often at high frequency, so that the voltage between the reactor electrodes can be reduced while maintaining the same efficiency of the plasma process. This means smaller dimensions of the power transformer's, as well as greater homogeneity of discharge without sparks or arcing.

B. GAD plasma reactor

A key advantage of GAD is its capability to generate NTP directly within polluted gases at atmospheric pressure and under conditions matching those of exhaust gas emission, eliminating the need for prior gas treatment. Figure 2 illustrates a schematic of the GAD plasma reactor electrodes, along with its equivalent electrical circuit and the theoretical voltage and current waveforms for a two-electrode GAD system.

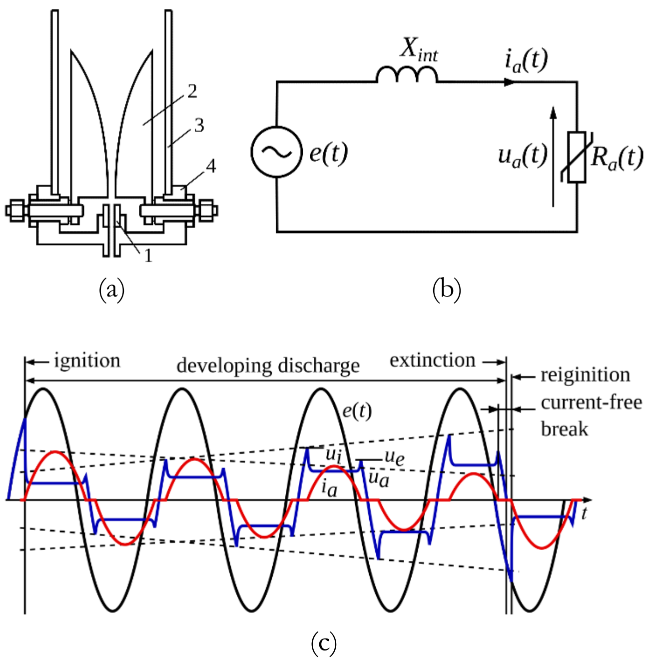

Figure 2: GAD PR electrode sketch (a) and equivalent circuit (b), theoretical voltage and current waveforms of the two-electrode GAD reactor (c) [2], where: 1 - nozzle for introducing process gas, 2 - high-voltage electrode, 3 - glass tube, 4 – body; $e(t)$ – PS voltage, X_{int} - internal reactance of the PS, R_a -non-linear resistance of the GAD PR, u_a – GAD voltage, i_a – GAD current, u_i - GAD ignition voltage, u_e - GAD extinction voltage.

The GAD PR in a PSS operates as a nonlinear resistive load, which often requires an auxiliary ignition system depending on the type and composition of the working gas. Once ignition occurs, it is crucial to rapidly and efficiently limit the reactor current to preserve non-thermal discharge conditions. The PSS for a GAD-based reactor should function as a true current source. The discharge current ia(t) is approximately sinusoidal, while the post-ignition voltage ua(t) remains nearly constant, between 1.5 – 1.6 kV when air is used as the working gas [3,4].

C. APPJ reactors

APPJ-type reactors are designed to produce stable, low-temperature plasma capable of exerting targeted effects on objects of various shapes and sizes. These reactors are commonly used in applications such as biological decontamination, medical treatments, and surface modification [5,6,7]. Plasma is typically generated within a nozzle, and a forced gas flow carries it out of the reactor toward the object being processed, forming a uniform glow discharge for effective plasma-chemical interaction. The design of APPJ plasma reactors uses solutions in which one of the electrodes is covered with DB, as in DBD PR, or with metal electrodes, as in GAD reactors. Various strategies are currently employed in APPJ technology to maintain non-thermal plasma conditions at atmospheric pressure.

These include optimizing gas flow parameters, configuring the geometry of the electric field, and selecting an appropriate power supply system [8–11].

III Power supply systems of plasma reactors with DBDs and GADs

Systems for generating non-thermal, non-equilibrium plasma can be powered using DC, pulsed, or sinusoidal voltages, with operating frequencies ranging from a few hertz, through radio frequencies (RF), up to several kilohertz or even hundreds of megahertz in the case of microwave plasma reactors. The power supply systems (PSS) for such plasma reactors typically include voltage conversion components – such as high-voltage transformers and magnetic switches (chokes) – as well as frequency converters, including thyristor and transistor inverters, pulse generators, and magnetic frequency converters. Power supply systems for APCP-generating plasma reactors must fulfill a range of specific requirements, including: (1) the type of electrical discharge used for plasma generation; (2) the chemical composition and physical properties of the working gas; (3) the pressure conditions within the discharge chamber; (4) the geometry of the discharge components; (5) the necessity to reliably initiate and sustain cyclic reactor operation post-ignition; (6) key electrical parameters such as power, voltage, frequency, number of phases, and output impedance; and (7) additional components that enhance compatibility with the electrical grid, including frequency filters and reactive power compensation systems. The article reviews the design of NTP generator power systems and their selected applications.

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