

Article

Analysis of Plasma Reactor Interaction with the Power Grid Depending on the Power Supply Design

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Abstract: In this paper, the collaboration of a GlidArc-type plasma reactor with four dedicated power supplies was analysed. Each power supply is characterised by a different design solution. Plasma generation by electrical discharge requires a careful analysis of the power supply design, its operating characteristics, currents, voltages and frequencies. Although the power supplies tested have similar abilities and provide similar power supply parameters, different plasma reactor performance characteristics are obtained for each of them. The results indicate that some power supply parameters were overestimated or underestimated at the design stage. Some of the power supplies tested under plasma reactor load also show poor interaction with the mains. The interaction of the power supplies with the plasma reactor and the mains supply is strongly influenced by the type of plasma gas. Analyses indicate that an optimally designed power supply should combine the solutions contained in each of the power supplies tested.

Keywords: plasma reactor; GlidArc; gliding arc; power supply; plasma; electric discharge; electric arc



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1. Introduction

Plasma is used in a number of technological processes, including cutting, sputtering of coatings, gas and surface decontamination, production of carbon nanotubes, and melting of steel. The parameters of the technological process dictate use of plasma. For technical purposes, low-temperature plasma is produced in devices called plasma reactors, of which there are many designs [1–5]. The predominant method of plasma generation in these devices is electrical discharge in a gas. Occasionally, microwave, laser, induction or capacitive plasma generators are encountered.

The possibilities for modifying plasma parameters in plasma reactors are limited [6–8]. It is possible to modify the discharge parameters by: (1) changing the shape of the electrodes, (2) changing the distance between the electrodes, (3) choosing the material from which the electrodes are made, and/or (4) choosing the shape of the discharge chamber. These methods often involve redesigning the plasma reactor and making changes to it or building a new reactor.

Additional possibilities for shaping the plasma parameters are provided by the plasma reactor's gas supply system. By: (1) controlling the inflow of plasma-generating gas, (2) selecting the chemical composition of the plasma-generating gas, and/or (3) changing the gas pressure in the discharge chamber [9–11], plasma parameters can be easily and continuously influenced.

In the main, it is the power supply system that determines the plasma parameters and the application possibilities of the plasma reactor [12–14]. Shaping the plasma parameters is possible through: (1) selecting the voltage between DC and AC, (2) selecting the frequency of the supply voltage, (3) selecting the voltage value, (4) selecting the voltage shape, (5) selecting the current value, and (6) influencing the harmonic content of the voltage and current. A power supply system that would allow the regulation of all these parameters

would have a complex design, which would translate into high manufacturing costs, high failure rates, high troubleshooting costs, susceptibility to interference, and complex operation. In most processes in which plasma reactors are used, extensive adjustment of the power supply parameters is not required. With a well-recognised and repeatable plasma process, it is possible to design a power supply that does not require any adjustment. Low manufacturing costs, low failure rates and simple operation are the most appreciated features of plasma reactor power supplies. The design of the power supply system determines the correct operation of the plasma reactor, its interaction with the power supply grid, and its impact on other equipment and people. The selection of the power system is not simple, since plasma reactors are strongly non-linear loads with stochastically varying parameters. Plasma reactors generate strongly electromagnetic interference, significant overvoltage and a large number of higher harmonics in the voltage and current [15–17]. Due to their low arc resistance, plasma reactors strongly loading the power systems [18,19].

Due to the structural diversity of plasma reactors, even within a single reactor type, and the variety of plasma processes carried out with them, it is difficult to rank these devices in terms of technical parameters. As a result, there are no guidelines for designing power systems for the entire multitude of plasma reactors.

Plasma generation by electrical discharge requires careful selection of the power supply system topology, its operating characteristics, and values of currents, voltages and frequencies [20,21]. In order to obtain good operation and control characteristics of a plasma reactor, specialised power supply systems, individually designed for a specific reactor and a specific plasma process, should be used [22,23]. From an operational, engineering and economic point of view, such an approach is unfavourable. Efforts are therefore being made to develop power systems that give the possibility of powering the widest possible range of plasma reactors, even if at the expense of lowering the efficiency of the plasma process.

In this paper, four designs of power supply systems dedicated to powering three-phase GlidArc-type plasma reactors were studied [24]. The power supplies under study were created in the Department of Electrical Engineering and Electrotechnologies at Lublin University of Technology for research projects on plasma applications in technology and industry. These power supplies have similar abilities and provide similar parameters to power the reactors but differ in design and operating principle. The differences in the design of the power supplies are due to the different requirements that were placed on them by the scope or nature of the work carried out in the various research projects, such as: regulating the frequency of the voltage supplying the reactor, increasing or decreasing the harmonic content of the voltage, increasing the dissipation reactance of the transformers, and the ability to control the discharge current. The parameters of the power supplies are selected to work with any GlidArc-type three-phase plasma reactor of no more than 9 kVA. The power supplies are designed so that any modifications to the plasma reactor (change of electrode shape, change of electrode material, change of process gas, etc.) do not affect the operation of the power supplies to an extent that would impair the reactor's power supply parameters. Despite providing a high degree of universality to the power supplies, it was noted during the course of plasma research that the power supplies have disadvantages in different areas of plasma reactor operating characteristics or applications. These observations became the genesis for a detailed study of how power supplies work with GlidArc-type plasma reactors. The control characteristics of the power supplies and their efficiency were analysed. Tests were carried out for the discharge burning in the four most commonly used plasma-forming gases: argon, helium, nitrogen, and air. The results obtained made it possible to rank the power supplies studied in terms of their efficiency in cooperation with the GlidArc plasma reactor. Attention was drawn to the advantages and disadvantages of the solutions used in the power supplies, and conclusions were drawn regarding the design of an optimal power supply system.

2. Plasma Reactor

A three-phase plasma reactor with gliding arc discharge of the GlidArc type [25] with the design shown in Figure 1 was used in the study. The reactor design parameters are displayed in Table 1. This reactor is used for gas decontamination processes, e.g., air pollutants generated in an iron foundry during the product coating process.

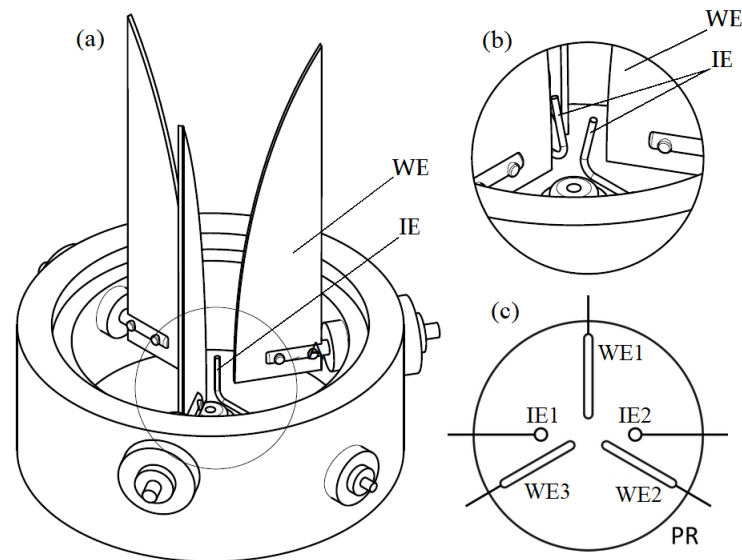


Figure 1. GlidArc-type plasma reactor, (a) overview drawing, (b) system with one ignition electrode, (c) system with two ignition electrodes, WE—working electrodes, IE—ignition electrodes.

Table 1. Technical parameters of the plasma reactor.

Number of working electrodes	3
Number of ignition electrodes	1 or 2
Height/width/thickness of working electrodes	140 mm/30 mm/2 mm
Working electrode spacing, bottom/top	5 mm/50 mm
Working electrode material	steel 0H18N9
Ignition electrode material	tungsten, wire Ø1 mm
Height of the discharge chamber	500 mm
Discharge chamber diameter	114 mm
Discharge chamber material	quartz glass
Material of the electrode clamping ring	aluminium PA6 (2017A)
Electrode holder and current bushings	copper DIN CuCrZr
Insulation of electrode holders	ceramics AL-70
Gas inlet nozzle	Ø5 mm

The reactor has three knife-shaped metal working electrodes arranged around the axis of the cylindrical discharge chamber with a 120° spacing between them. Each electrode is supplied from a separate phase of the three-phase grid. The supply voltage to the working electrodes should not exceed 1.5 kV at a frequency of 50 Hz, and the supply current should be less than 5 A. With such supply parameters, a plasma is obtained which has the property of decontaminating air.

With the electrodes used in the reactor and the distances between them, a voltage value of 1.5 kV is not sufficient for spontaneous ignition of the discharge. Therefore, the reactor is additionally equipped with one or two ignition electrodes made of thin metal wire. The purpose of these electrodes is to initiate an electrical discharge at the working electrodes. The ignition electrodes are supplied with voltages up to 15 kV with a minimum frequency of 50 Hz but not exceeding 20 kHz, with a current value not exceeding 350 mA. These power supply parameters are not sufficient to ignite the arc discharge at the ignition electrodes, but they do allow the electric spark to jump over. A single ignition electrode initiates the spark discharge to the working electrodes. The initiated spark channels develop into an arc discharge due to the increase in power supplied to them from the working electrodes. With two ignition electrodes, the spark discharge burns between the ignition electrodes without the involvement of the working electrodes. These discharges reduce the electrical strength of the space between the working electrodes, which allows an arc discharge to ignite between them at reduced voltage.

The operation of the GlidArc reactor is cyclic. Initiated by the ignition discharge, the right discharge burns on the working electrodes under the influence of the gas-dynamic forces caused by the plasma-forming gas flowing into the discharge chamber, and rises along the electrodes, increasing its length and volume. The nature of the discharge changes, moving from a short arc to a discharge with parameters similar to those of a glow discharge. The parameters of the generated plasma also change [26,27]. The discharge is extinguished when the power supplied from the power system cannot compensate for the energy losses of the intensively cooled and blown discharge. The end result of the plasma reactor cycle is a plasma column. As soon as the discharge is extinguished, it is rebuilt with ignition electrodes and the reactor cycle repeats. The length of the reactor cycle depends on its design parameters, the parameters of the plasma gas and the parameters of the electrical power supply system [28].

3. Electrical Power Supply System

The most important device cooperating with the plasma reactor is the power supply system. Properly selected, it guarantees stable parameters of the generated plasma, high efficiency of the plasma process and low interference generated by the plasma reactor. There are many plasma reactor power supply solutions dedicated to specific equipment or processes. The cooperation of the GlidArc plasma reactor was analysed with four different power supply systems. The power supplies under study were created in the Department of Electrical Engineering and Electrotechnologies at Lublin University of Technology for research projects on plasma applications in technology and industry. This research focused on the possibilities of using plasma generated in GlidArc-type reactors. However, there was no detailed analysis of the cooperation of this type of reactor with power supply systems.

The basic element of all the power supplies discussed is the transformer. Sometimes the transformer itself, when properly designed, makes a good power supply. Such a power supply is shown in Figure 2. The power supply design uses three single-phase transformers T_1 , T_2 and T_3 connected in a YNy three-phase connection circuit. These transformers form the T-circuit supplying the working electrodes WE_1 , WE_2 and WE_3 of the plasma reactor. The transformers are characterised by cores made of the amorphous material Metglas 2605SA1. The primary and secondary windings are concentrically wound in a manner typical of most transformers. A separate electrical circuit IS is used to power the IE_1 and IE_2 ignition electrodes of the plasma reactor. This circuit uses a high-frequency electronic high-voltage inverter. The parameters of the power supply circuit are given in Table 2. The letter designation TPS is adopted for this power supply.

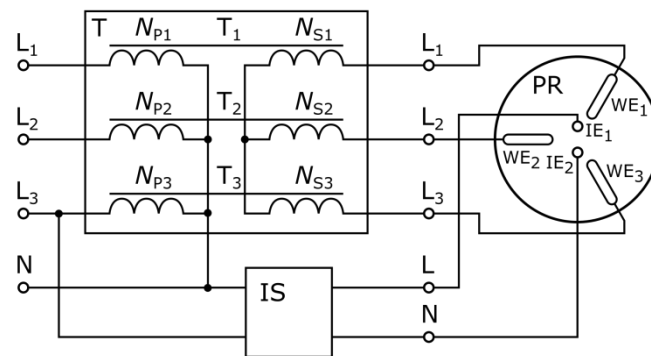


Figure 2. Transformer power system TPS, PR—plasma reactor, T—reactor working electrodes power circuit, IS—ignition electrodes power circuit, N_{P1} , N_{P2} , N_{P3} —primary windings, N_{S1} , N_{S2} , N_{S3} —secondary windings, WE_1 , WE_2 , WE_3 —plasma reactor working electrodes, IE_1 , IE_2 —reactor ignition electrodes.

Table 2. Parameters of the reactor working electrode supply circuits.

Power Supply Type	TPS	ITPS	IFCTPS	PCS
Power	13.8 kVA	9 kVA	11 kVA	13.8 kVA
Supply voltage	230 V	230 V	230 V	230 V
Supply current	20 A	20 A	16 A	20 A
Output voltage	1.2 kV	1.3 kV	1.2 kV	1.2 kV
Output current	3 A	5 A	2.4 A	3 A
Output frequency	50 Hz	50 Hz	50 Hz	10 ÷ 200 Hz

An extension of the TPS power supply system is the system labelled PCS. In the PCS power supply system, transformers T_1 , T_2 and T_3 are supplied by an AC/DC/AC transistor converter, as shown in Figure 3. The converter allows the frequency of the reactor supply voltage to be adjusted between 10 and 200 Hz, and the reactor discharge current to be adjusted. Chokes with an inductance of 20 mH are installed between the transformers and the converter.

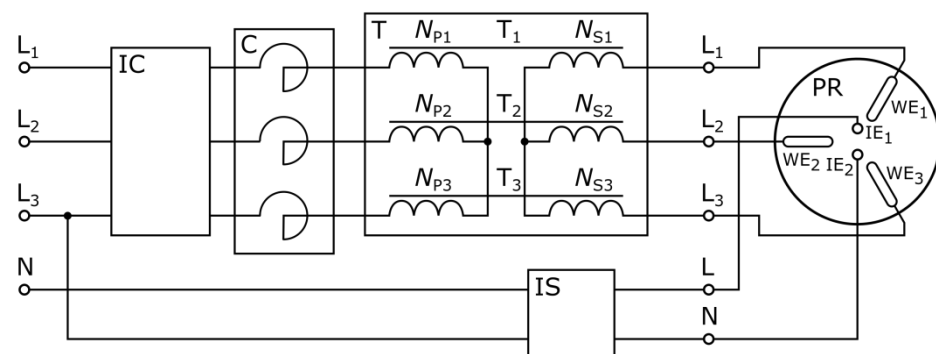


Figure 3. Converter power system PCS, PR—plasma reactor, T—reactor working electrodes power circuit, IS—ignition electrodes power circuit, C—chokes, IC—AC/DC/AC transistor converter, N_{P1} , N_{P2} , N_{P3} —primary windings, N_{S1} , N_{S2} , N_{S3} —secondary windings, WE_1 , WE_2 , WE_3 —plasma reactor working electrodes, IE_1 , IE_2 —reactor ignition electrodes.

The next power supply system to be tested was a system called ITPS, consisting of three suitably connected single-phase transformers, as shown in Figure 4. Three identical transformers T_1 , T_2 and T_3 were connected to form a three-phase connection system YNyn. These transformers form the power circuit for the working electrodes WE_1 , WE_2 and WE_3

of the plasma reactor. The fourth transformer T_4 is used to supply the ignition electrode IE_1 of the plasma reactor. The primary and secondary windings of this transformer are included in the neutral conductors of the system of transformers T_1, T_2 and T_3 . The cores of the transformers are made of ET 120-27 electrical sheet metal. The operating point of transformers T_1, T_2 and T_3 on the magnetisation characteristics of the cores was selected so that the cores operate at low saturation. As a result, a current containing the 3rd harmonic is taken from the grid. This current flows through the primary winding of transformer T_4 and a voltage of threefold frequency is induced in the secondary winding of this transformer.

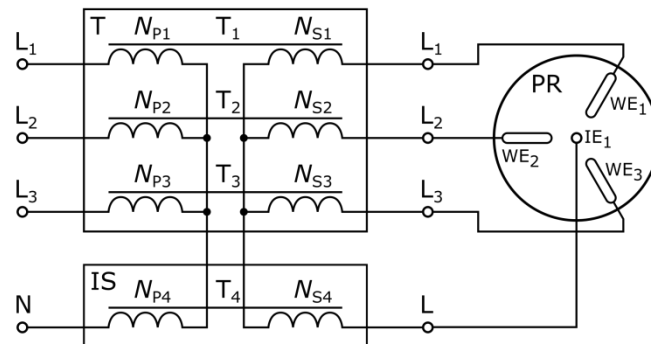


Figure 4. Integrated power system ITPS, PR—plasma reactor, T—reactor working electrode power circuit, IS—ignition electrode power circuit, $N_{P1}, N_{P2}, N_{P3}, N_{P4}$ —primary windings, $N_{S1}, N_{S2}, N_{S3}, N_{S4}$ —secondary windings, WE_1, WE_2, WE_3 —plasma reactor working electrodes, IE_1 —reactor ignition electrode.

The last power supply system tested, designated IFCTPS, uses a five-column transformer in its design (Figure 5). This system integrates the power circuit for the working electrodes of the plasma reactor and the power circuit for the ignition electrodes in a single transformer. The transformer core is made of ET 120-27 electrical sheet metal. The primary and secondary windings of the transformer are connected in a YNy three-phase connection arrangement. In typical three-phase transformer designs with five-column cores, the outer columns have no windings. In the case of the power supply in question, windings were wound on the outer columns of a five-column transformer to supply the plasma reactor ignition electrodes.

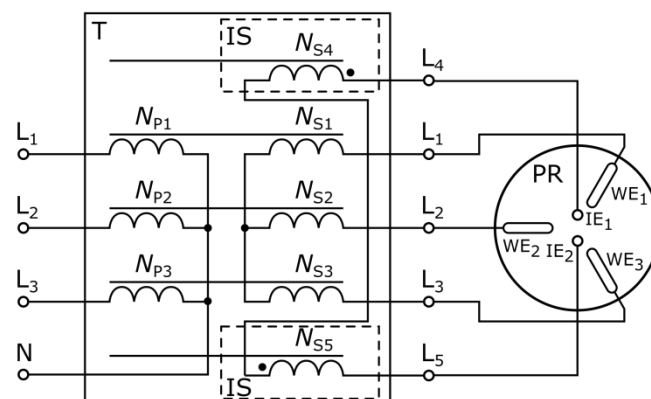


Figure 5. Power system with 5-column transformer IFCTPS, PR—plasma reactor, T—reactor working electrodes power circuit, IS—ignition electrodes power circuit, N_{P1}, N_{P2}, N_{P3} —primary windings, $N_{S1}, N_{S2}, N_{S3}, N_{S4}, N_{S5}$ —secondary windings, WE_1, WE_2, WE_3 —plasma reactor working electrodes, IE_1, IE_2 —reactor ignition electrodes.

The technical parameters of the power supply circuits discussed are summarised in Tables 2 and 3. Table 2 gives the technical parameters of the plasma reactor working

electrode power supply circuits and Table 3 gives the parameters of the plasma reactor ignition electrode power supply circuits.

Table 3. Parameters of the reactor ignition electrode supply circuits.

Power Supply Type	TPS	ITPS	IFCTPS	PCS
Ignition system	electronic	transformer	transformer	electronic
Supply voltage	230 V	–	–	230 V
Supply current	250 mA	–	–	250 mA
Output voltage	15 kV	10 kV	7.6 kV	15 kV
Output current	40 mA	200 mA	350 mA	40 mA
Output frequency	20 kHz	150 Hz	50 Hz	20 kHz

4. Measurement System

In order to carry out tests on the cooperation of the plasma reactor with different types of power supply systems, a test platform was built consisting of two circuits: (1) the electricity supply and (2) the plasma gas supply.

A schematic diagram of the system for measuring electrical quantities is shown in Figure 6. Measurements were made at the inputs and outputs of the power supplies under study. Currents of all phases, phase-to-phase voltages, harmonic content in currents and voltages, active, reactive and apparent powers, and power factor were measured. The measuring system was supplied from a three-phase 400 V grid via a 23.4 kVA ATS-FAZ3-23 autotransformer. The autotransformer allows regulation of the supply voltage in a range from 0 to 450 V. The measuring system consisted of Merazet LM-3 voltmeters, Mezaret LE-3 ammeters, Mezaret LW-1 wattmeters, Tektronix DPO3054 oscilloscope, Fluke Norma 5000 power analyser, Tektronix P6015A and TCP0030 measuring probes.

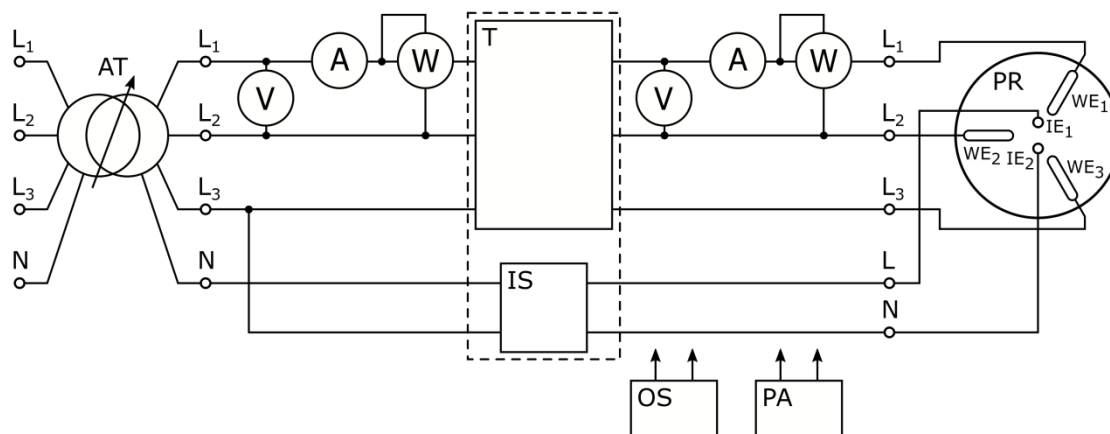


Figure 6. Measuring system for testing the cooperation of a plasma reactor with different types of power supplies, AT—autotransformer, V—voltmeter, A—ammeter, W—wattmeter, OS—oscilloscope, PA—power analyser, PR—plasma reactor, T—reactor working electrodes power circuit, IS—ignition electrodes power circuit.

An important part of the test platform is the system for supplying the plasma reactor with plasma-generating gases. The test installation consisted of four cylinders of technical gases containing argon, helium, nitrogen, and air (Figure 7). The type of plasma-generating gas introduced into the discharge chamber of the GlidArc reactor determines its performance characteristics [29]. Cylinder gas was fed to the gas inflow nozzle of the plasma reactor through Bronkhorst's EL-FLOW mass flowmeters and flow controllers: the F-202AV-M20-AAD-44-V with a flow rate of up to 15 m³/h, the F-201AV-50K-AAD-44-V with a flow

rate of up to 2 m³/h, and the F-201CV-1K0-AAD-44-V with a flow rate of up to 0.06 m³/h. These regulators allow precise mixing of the gases and control of their flow through the plasmotron nozzle. The volumetric flow rate of gases entering the plasmotron nozzle was measured during the study.

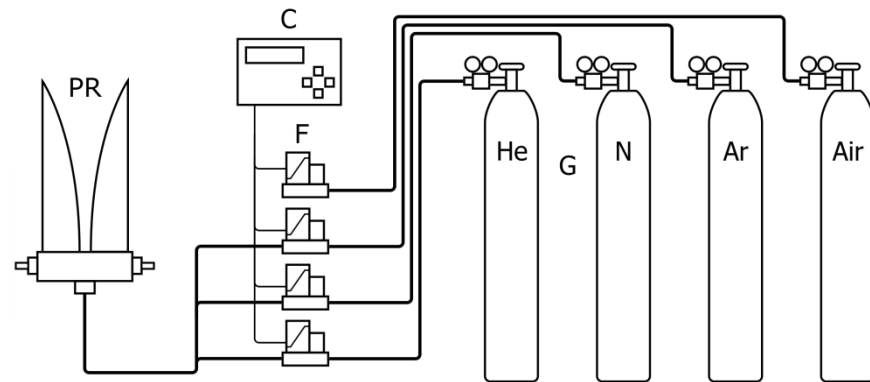


Figure 7. Plasma gas supply system, PR—plasma reactor, G—plasma gases, F—flow regulators, C—regulator setting and control system.

5. Test Results

To begin, the power supply units were tested for interaction with the grid under conditions when the outputs of the power supply units were not loaded. Measurements were carried out in the measurement system shown in Figure 6. The PR plasma reactor was disconnected from the circuit, leaving the output terminals of the L₁, L₂, L₃, L and N power supplies free.

The measurements of the electrical quantities taken from the grid by the power supply units are shown in Table 4. The table gives the rms values of the phase voltages U_1 feeding the power supplies, the currents taken by the power supplies from the mains I_1 , the active power P_1 , reactive power Q_1 and complex power S_1 taken, power coefficients $\cos\varphi$, and the harmonic content factors in the voltage $U_{1\text{THD}}$ and current $I_{1\text{THD}}$.

Table 4. Operating parameters of power supplies in no-load condition.

		ITPS	TPS	IFCTPS	PCS
U_1	V	237.4	238.3	234.4	234.9
I_1	A	0.998	0.012	0.068	0.826
P_1	W	67.61	7.95	14.11	335.41
Q_1	Var	707.24	3.27	37.71	476.63
S_1	VA	712.04	8.58	41.92	582.77
$\cos\varphi_1$	—	0.095	0.926	0.341	0.572
$U_{1\text{THD}}$	%	2.54	2.45	2.68	1.93
$I_{1\text{THD}}$	%	51.60	34.63	41.9	87.22

The TPS power supply has the lowest grid power consumption, with a complex power consumption of 8.58 VA. Simultaneously, this power supply has the best power factor of all the power supplies tested (0.926) and has low harmonic content ratios in voltage and current of 2.45% and 34.63%, respectively. The IFCTPS power supply performs slightly poorer in terms of the aforementioned parameters. The ITPS is the worst performer. In idle operation, it takes 712.04 VA from the grid with a power factor of just 0.095. In contrast, the PCS power supply has the highest harmonic content in current at 87.22%. This power supply also takes the second highest power from the grid at 582.77 VA. From the comparison presented, it is apparent that plasma reactor power systems using conventional

transformers, with a typically chosen operating point on the magnetisation characteristic, provide the best interaction with the grid.

The most important factor in the operation of the power supplies is their response under the load of the plasma reactor in which the arc discharge is burning. Example waveforms of single-phase voltages and currents at the inputs and outputs of power supplies loaded with an operating plasma reactor, obtained from oscilloscope measurements, are shown in Figures 8–11. The waveforms were obtained for a discharge burning in argon, whose volume flow through the plasmotron nozzle was $2.8 \text{ m}^3/\text{h}$.

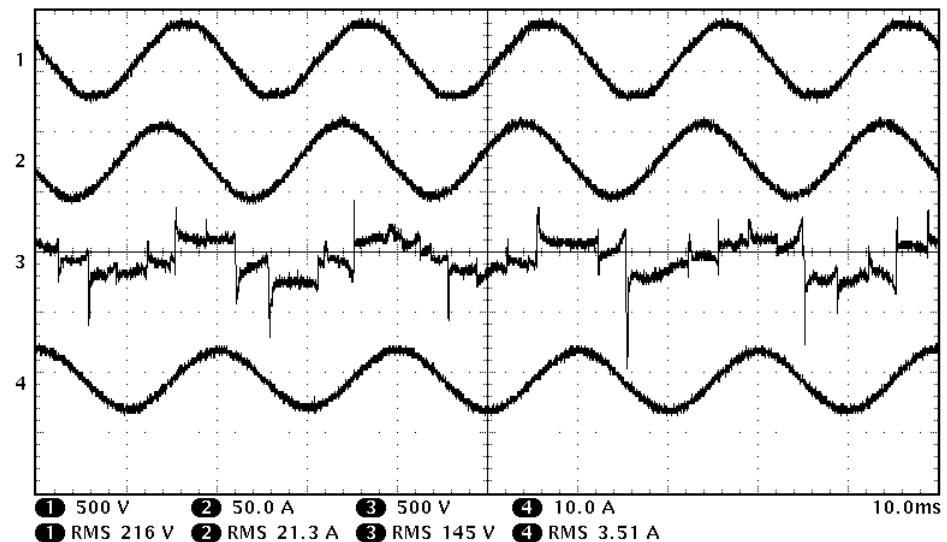


Figure 8. Current and voltage waveforms of the TPS power supply, 1—input voltage, 2—input current, 3—output voltage, 4—output current, plasma gas: argon, flow: $2.8 \text{ m}^3/\text{h}$.

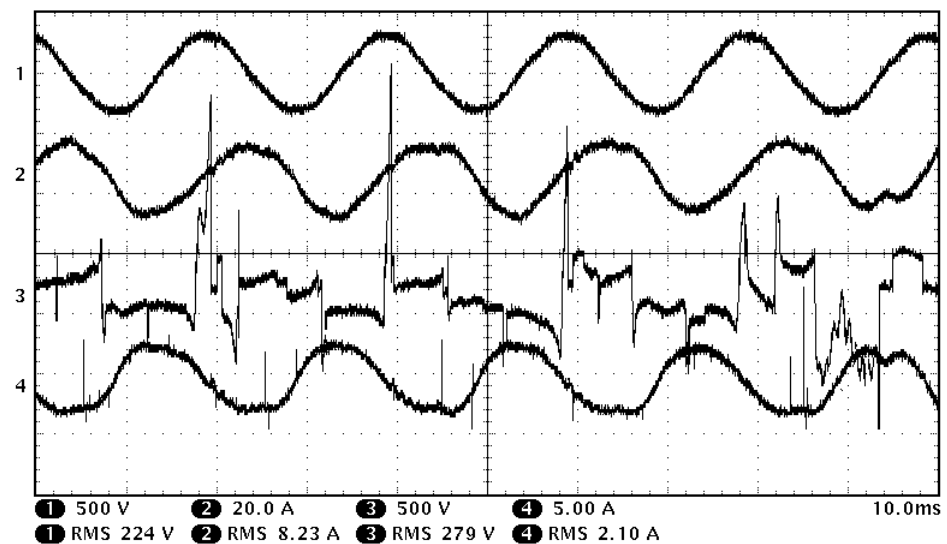


Figure 9. Current and voltage waveforms of the ITPS power supply, 1—input voltage, 2—input current, 3—output voltage, 4—output current, plasma gas: argon, flow: $2.8 \text{ m}^3/\text{h}$.

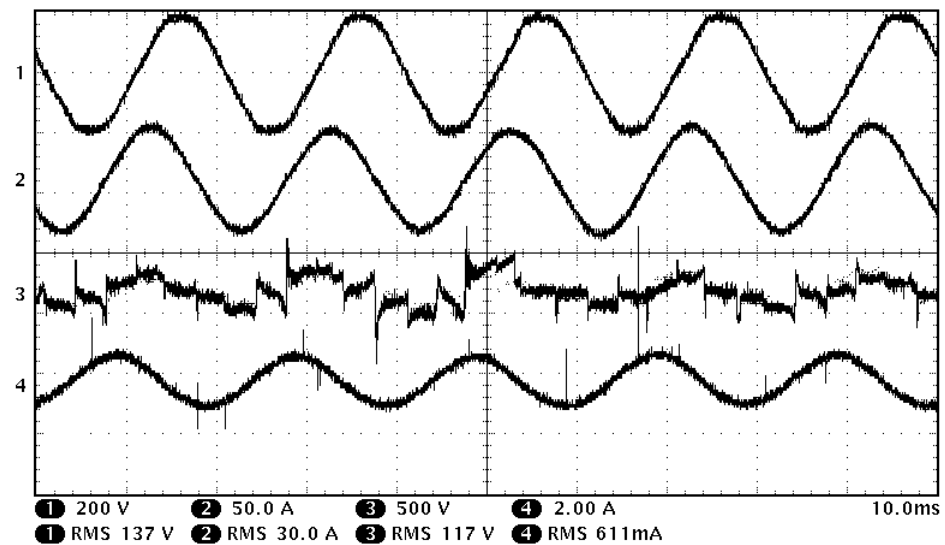


Figure 10. Current and voltage waveforms of the IFCTPS power supply, 1—input voltage, 2—input current, 3—output voltage, 4—output current, plasma gas: argon, flow: $2.8 \text{ m}^3/\text{h}$.

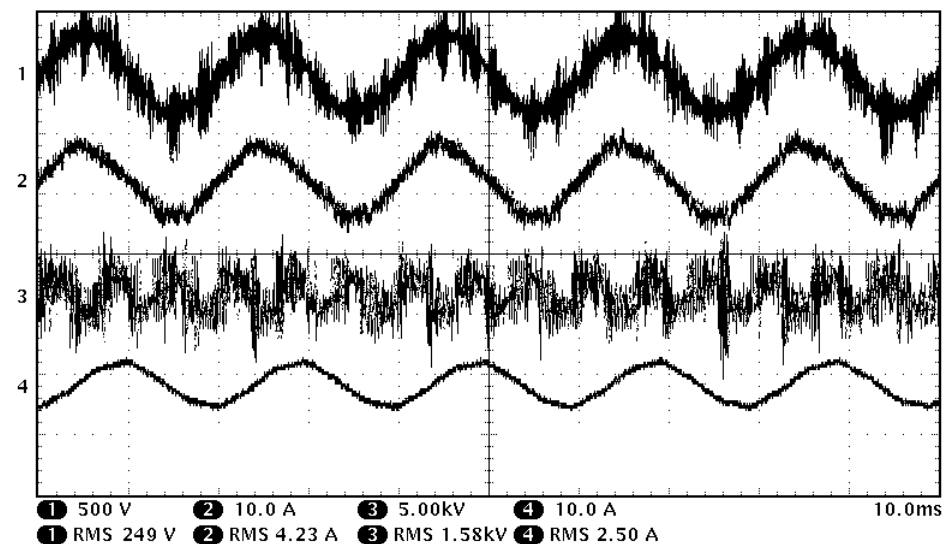


Figure 11. Current and voltage waveforms of PCS power supply, 1—input voltage, 2—input current, 3—output voltage, 4—output current, plasma gas: argon, flow: $2.8 \text{ m}^3/\text{h}$.

The voltage and current waveforms at the output of the TPS, ITPS and IFCTPS power supply shown in Figures 9–11 are typical of arcs burning in a three-phase system at low current and cooled intensively [30,31].

Of the gases used in measurement, argon provides the best conditions for ignition and development of a discharge in the reactor over the entire range of its flow control, and over the entire range of control characteristics of the electrical parameters of the power supplies. Despite superior argon characteristics, significant distortion of the output voltages of the tested power supplies is observed in the obtained oscillograms. Particularly large distortions are seen in the output voltage of the PCS power supply. In the case of the ITPS power supply, high value overvoltages are observed in the form of peaks accompanying the ignition of the reactor discharge. In the case of this power supply, distortion of the arc current is also evident. Poorer performance of the power packs with the plasma reactor is obtained when helium is used as the plasma-generating gas.

The plasma-generating gas that is most problematic in the interaction of the investigated power packs with the plasma reactor is nitrogen. Nitrogen is a gas with a high

ignition voltage and discharge support. Co-operation of power supplies with a reactor in which the discharge burns in nitrogen is unfavourable due to high discharge instability, a large number of disturbances in the voltage and current waveforms, and poor control characteristics. Slightly better performance is obtained with air as the plasma-forming gas. These problems arise for several reasons: (1) the design of power supplies with the assumption that the main plasma-generating gases will be argon and helium, (2) the adoption of an output voltage of power supplies not much larger than the ignition voltage of the discharge in nitrogen, (3) the limitation of the value of the discharge current which translates into a low arc temperature, (4) the susceptibility of the arc discharge to stochastic changes in position and length, and/or (5) the disturbance of the gas flow through the reactor discharge chamber caused by the reactor structural elements and the electrical discharge, worsening locally and temporarily the conditions for ignition and burning of the discharge [32,33].

Figures 12–15 show the control characteristics of the reactor supplied from the test power supplies when the discharge burns in argon, helium, nitrogen and atmospheric air. The characteristics were obtained for a volumetric gas flow rate through the plasmotron nozzle of 1.6 m³/h.

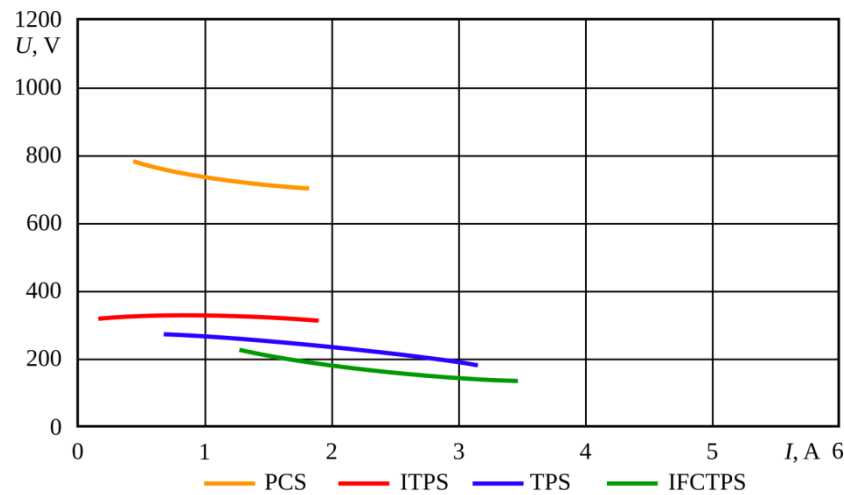


Figure 12. Control characteristics of the tested power supplies loaded with plasma reactor, plasma gas: argon, volumetric flow rate: 1.6 m³/h.

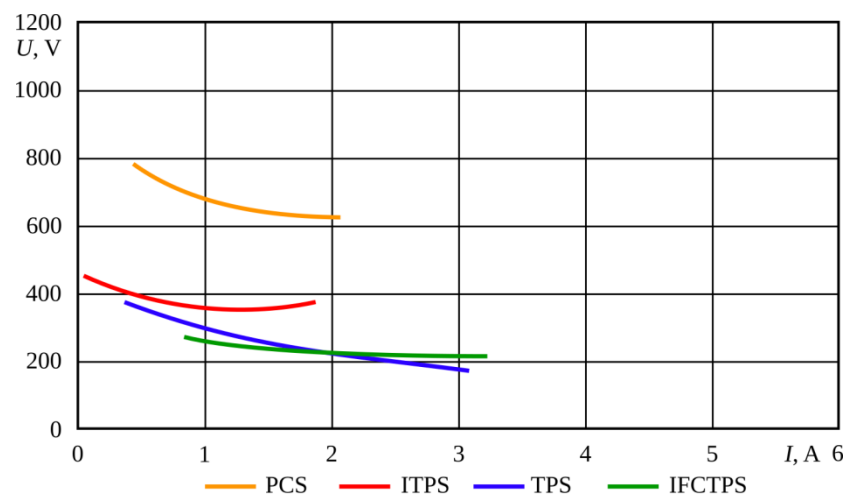


Figure 13. Control characteristics of the tested power supplies loaded with plasma reactor, plasma gas: helium, volumetric flow rate: 1.6 m³/h.

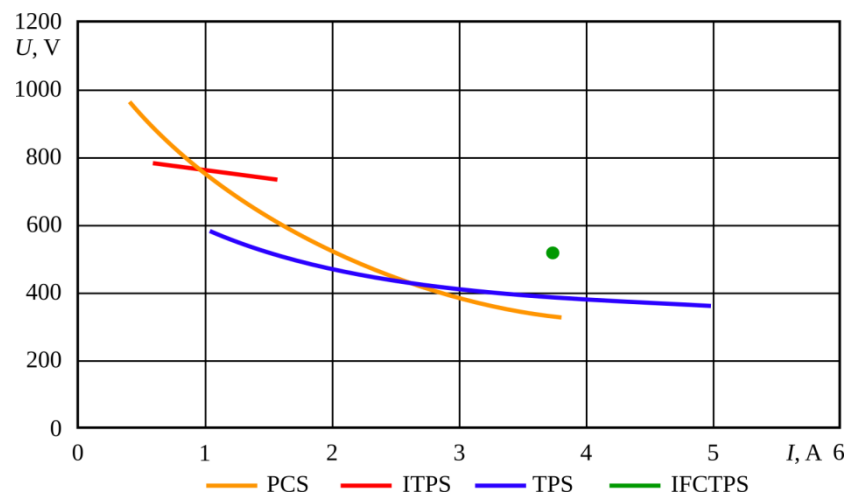


Figure 14. Control characteristics of the tested power supplies loaded with plasma reactor, plasma gas: nitrogen, volumetric flow rate: $1.6 \text{ m}^3/\text{h}$.

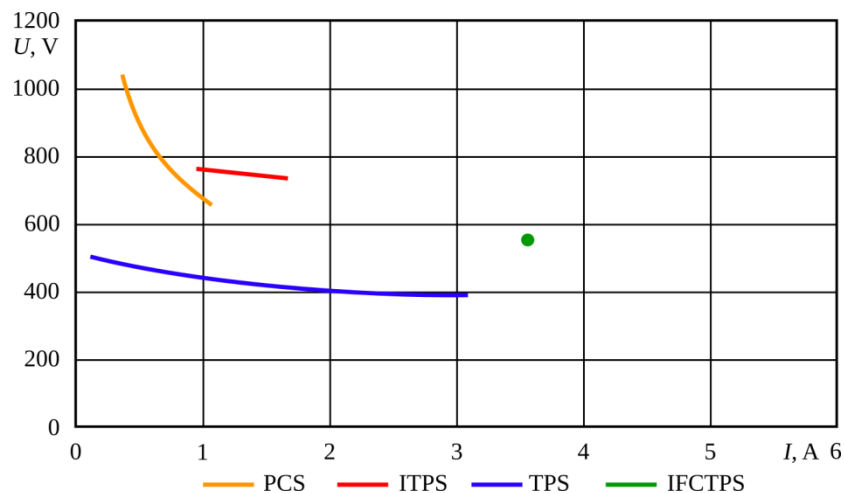


Figure 15. Control characteristics of the tested power supplies loaded with plasma reactor, plasma gas: air, volumetric flow rate: $1.6 \text{ m}^3/\text{h}$.

In the case of an electric discharge burning in argon, all power supplies tested showed good regulation properties (Figure 12). The IFCTPS and TPS power supply have the widest range of discharge current regulation. The worst performer in this respect is the PCS converter power supply. This power supply is also characterised by the highest value of the voltage at which the discharge in the plasma reactor burns. The value of the discharge burning voltage when the reactor is supplied from the PCS power supply is about 4 times higher compared to the IFCTPS power supply.

The low voltage values at which the discharge in the reactor burns, together with the high excess voltage supplying the working electrodes of the reactor provided by the TPS, ITPS and IFCTPS power supplies, allows the power supplied to the plasma reactor to be regulated using an autotransformer. The wide current control ranges available with these power supplies allow the plasma temperature to be influenced to suit the requirements of the plasma process being carried out. The low voltage and current values at which the discharge burns when the reactor is supplied from TPS, ITPS, and IFCTPS power supplies make it possible to obtain the low-temperature plasma required in many plasma-chemical processes.

When changing the plasma-generating gas to helium, no significant changes in the current control ranges were observed for all the power supplies tested (Figure 13). In the

case of the TPS, ITPS, and IFCTPS power supplies, there is a slight but noticeable increase in the voltage at which the electrical discharge in the plasma reactor burns. In the case of the PCS converter power supply, the helium discharge burns at voltage values similar to the burning voltage of the argon discharge.

When the discharge burns in nitrogen in the plasma reactor, the control characteristics of the ITPS and IFCTPS power supply deteriorate (Figure 14). For the ITPS power supply, the discharge burns at about twice the voltage as when argon and helium are used as plasma gases. The control range of the discharge current in the case of discharge in nitrogen is also shortened by a factor of two. Even worse is the control characteristic of the IFCTPS power supply, which is reduced to a single point. With this power supply, the discharge in the plasma reactor when the plasma gas is nitrogen burns only at 550 V and 3.75 A. The TPS and PCS power supplies have the best control characteristics for discharge in nitrogen.

Changing the plasma gas to atmospheric air does not significantly change the control characteristics of the feeders obtained for nitrogen (Figure 15), likely due to the fact that nitrogen makes up about 78% of the air composition.

The study shows that the apparent powers for which all power supplies were designed are significantly higher than the maximum arc power generated in the plasma reactor. Table 5 shows the ranges of discharge powers than can be obtained in the plasma reactor for the different plasma-generating gases and compares them with the rated powers of the power supplies tested. Analysing the percentage ratio (Table 6) of the maximum power obtained in the burning discharge in the individual gases to the power rating of the power supplies, it is found that the highest ratios were achieved for the ITPS power supply of 8.9% for argon, 7.8% for helium, 13.3% for nitrogen and atmospheric air. The worst performer in this respect is the TPS power supply where 4.3% is achieved for argon and helium, 3.6% for nitrogen, and 8% for air. For the IFCTPS and PCS power supplies, these ratios are 5.5% and 10.9% for argon, 5.5% and 5.1% for helium, 4.5% and 7.2% for nitrogen, and 10.9% and 8.7% for air, respectively.

Table 5. Power supply ratings and discharge power ranges for different plasma gases.

Power Supply Type	TPS	ITPS	IFCTPS	PCS
Rated power	13.8 kVA	9 kVA	11 kVA	13.8 kVA
Power for argon	0.2–0.6 kVA	0.1–0.8 kVA	0.4–0.6 kVA	0.1–1.5 kVA
Power for helium	0.3–0.6 kVA	0.3–0.7 kVA	0.3–0.6 kVA	0.3–0.7 kVA
Power for nitrogen	0.1–0.5 kVA	0.5–1.2 kVA	0.5 kVA	0.9–1.0 kVA
Power to the air	0.1–1.1 kVA	0.5–1.2 kVA	1.2 kVA	0.5–1.2 kVA

Table 6. Percentage ratio of maximum power obtained in the discharges to the power ratings of the Power supplies.

Power Supply Type	TPS	ITPS	IFCTPS	PCS
Argon	4.3%	8.9%	5.5%	10.9%
Helium	4.3%	7.8%	5.5%	5.1%
Nitrogen	3.6%	13.3%	4.5%	7.2%
Air	8%	13.3%	10.9%	8.7%

A comparison between the rated powers for which the power supplies are designed and the maximum discharge powers burning in the plasma reactor shows that the power supplies operate in a state of significant underloading. This underload translates into low power factor and low efficiency of the power supplies. Table 7 shows the maximum efficiencies with which each power supply operates depending on the type of plasma gas. Efficiencies are expressed as the ratio of the electrical discharge power burning in

the plasma reactor to the power taken from the grid supplying the power supplies. The TPS power supply achieves the highest efficiency of all the power supplies tested at over 70% when the electrical discharge is in nitrogen and air. The TPS power supply is also the power supply that achieves the highest average efficiency calculated for all gases. The second highest average efficiency value is achieved by the PCS power supply. The PCS power supply achieves higher efficiencies than the TPS power supply for the discharge burning in argon and helium.

Table 7. Efficiencies of power supplies for a burning discharge in different plasma gases.

Power Supply Type	TPS	ITPS	IFCTPS	PCS
Maximum efficiency for argon	25%	18%	35%	36%
Maximum efficiency for helium	26%	20%	20%	40%
Maximum efficiency for nitrogen	72%	20%	18%	20%
Maximum efficiency for air	70%	28%	25%	28%

The analysis of the harmonic content of the voltage and current drawn from the grid by power supplies loaded with the plasma reactor was carried out. For all the power supplies analysed, a large value of the I_{THD} coefficient of harmonic content in current was obtained. In contrast, a relatively small value of the harmonic content factor U_{THD} was obtained in the voltage. Table 8 shows the measured harmonic content ratios. The highest current harmonic content factor values were recorded for the PCS power supply for all plasma gases. For this power supply, the I_{THD} exceeds 146% for the air burning discharge and reaches 163% for the argon discharge. In other power supplies, the value of this coefficient strongly depends on the type of plasma gas. For example, the IFCTPS power supply achieves an I_{THD} value of 148% for discharge in nitrogen, 133% for discharge in air, only 24.7% for discharge in argon, and 19.5% for discharge in helium; 19.5% is also the lowest I_{THD} value recorded for all power supplies. In contrast, the highest value of this coefficient was recorded for the TPS power supply when the electrical discharge burned in helium.

Table 8. Harmonic content ratios.

Power Supply Type	Parameter	Gas			
		Argon	Helium	Nitrogen	Air
TPS	I_{THD}	24%	184%	92.4%	64%
	U_{THD}	3.54%	3.3%	3.83%	4%
ITPS	I_{THD}	61.2%	36.9%	77.3%	75.2
	U_{THD}	2.64%	2.43%	3.19%	1.2%
IFCTPS	I_{THD}	24.7%	19.5%	148%	133%
	U_{THD}	7.86%	4.54%	3.72%	3.71%
PCS	I_{THD}	163%	148.4%	148.3%	146.7%
	U_{THD}	5.3%	5.07%	4.78%	4.75%

6. Conclusions

The article investigates the cooperation of a plasma reactor with four types of power supplies in electricity. These power supplies were constructed at the Department of Electrical Engineering and Electrotechnologies of Lublin University of Technology for the purpose of carrying out research projects on plasma applications in technology and industry. However, no detailed research had been conducted on their interaction with the plasma reactor.

From the current analysis, it appears that all the power supplies tested exhibit poor interaction with the plasma reactor, where the discharges burn in nitrogen or in air. In nitrogen and air, the discharges burn unstably which manifests as interference in the plasma reactor's operating cycle. These disturbances are transferred to the power supplies, degrading their operational parameters. In the case of IFCTPS and ITPS power supplies, the discharge burning in nitrogen and air is also characterised by a narrow discharge power control range.

In the case of argon and helium discharges, all the power supplies tested were able to achieve cyclic and stable discharges in the plasma reactor with a wide range of power control.

The measurements show that the primary design defect of the power supplies tested is an overestimation of their power ratings in relation to the maximum discharge power burning in the reactor.

Of all the power supplies tested, the PCS converter power supply exhibits the greatest number of characteristics predisposing it to powering plasma reactors. This power supply does not have the best control characteristics of all the power supplies tested, but it guarantees correct burning of the discharge in the plasma reactor for all plasma gases. A major advantage of the PCS power supply is the ability to shape the plasma parameters by varying the frequency of the supply voltage. In the case of this power supply, an intermediate transformer has a major influence on its interaction with the plasma reactor. In the research carried out, the TPS transformer power supply system played the role of the intermediate transformer. The TPS power system had the best interaction with the plasma reactor of all the power supplies tested. When combined with the PCS, problems were generated by the electronic ignition system. This system is not only characterised by a high failure rate, but also generates high conducted interference, disturbing the operation of the AC/DC/AC converter.

From the analysis, it can be concluded that the best power supply design would be characterised by a configuration consisting of an AC/DC/AC transistor converter coupled to a five-column transformer with wound end columns. The core of such a transformer would have to be made of an amorphous material, such as the Medglas 2605SA1 type. A core made of amorphous material has a greater range of transmitted frequencies compared to ET sheet cores, which translates into better power transfer from the AC/DC/AC converter to the plasma reactor. Interaction of the IFCTPS power supply of the design presented in this paper with the transistor AC/DC/AC converter is problematic due to the low dissipation reactance of the five-column transformer and was therefore not tested. To make this cooperation possible, the phase windings of a five-column transformer would have to be made in the form of alternating primary and secondary disc windings, guaranteeing the desired dissipation reactance. With the appropriate design of the phase windings, it also seems possible to eliminate the chokes present in the output circuits of the AC/DC/AC converter.

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