Chosen Aspects of the Electromagnetic Compatibility of Plasma Reactors with Gliding Arc Discharges

Paweł Mazurek

Department of Electrical Engineering & Electrotechnologies, Lublin University of Technology
Nadbystrzycka 38A, 20-618 Lublin, Poland; p.mazurek@pollub.pl

Received: 20 April 2020; Accepted: 27 May 2020; Published: 29 May 2020

Featured Application: The results of the research presented in the article indicate the existence of many electromagnetic interferences in the plasma reactor installation. It is important to prevent them, already while designing the installation and using it. It is important for the safety of people and equipment.

Abstract: This paper presents an analysis of electromagnetic disturbance interactions inside the three-phase gliding arc plasma generation installation. This is the main part of the electromagnetic compatibility analysis of the reactor installation. All elements of the nonthermal plasma installation are described from the point of view of disturbance generation and their influence on the power supply system. The analysis is based on the results of tests carried out in accordance with the guidelines of the electromagnetic compatibility (EMC) Directive and harmonised standards. The disturbances measured are large, over 20 dB above the limits. The disturbances measured allow valid conclusions to be reached in relation to this type of installation. The implication is the need for plasma reactors designed with elements that reduce radiated and conducted interference.

Keywords: electromagnetic compatibility; electromagnetic disturbances; electromagnetic emission; plasma reactor; GlidArc

1. Introduction to Electromagnetic Compatibility

Electrical equipment and systems process electrical energy and share the space of the electromagnetic environment by interacting with each other. These interactions are often undesirable. Such phenomena are called “electromagnetic disturbance” and designate any electromagnetic phenomenon which may degrade the performance of equipment. Electromagnetic disturbance may be electromagnetic noise, an unwanted signal or a change in the propagation medium itself. The problems of limiting disturbance emissions and designing devices with a good level of immunity to them are defined by electromagnetic compatibility. Electromagnetic compatibility (EMC) means the ability of equipment to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to other equipment in that environment [1–4].

Compliance with the requirements of electromagnetic compatibility by every electric device brings profits in terms of safety of their use. It is also a necessary legal condition to prove compliance with the requirements of European Union directives (e.g., [1]).

Assessment of compliance with the requirements of the EMC Directive [1] is performed as technical tests of the equipment, which are given in harmonised standards. A positive assessment gives a presumption of conformity with essential requirements. The technical tests are intended to show whether the electrical equipment is not a source of hazardous electromagnetic disturbance and whether it is immune to electromagnetic disturbance in the environment.
These interactions are shown in Figure 1. Objects A and B are real devices that work in some environment. When measuring the compatibility of object A, a system of measuring and testing equipment is introduced instead of object B. This system is compliant with the CISPR 16 series of international standards.

The maximum levels of disturbance emitted by the equipment are strictly defined in the standards for that equipment by the value of the electromagnetic field strength in the environment of the object. The standards describe electromagnetic environments and their division into: (a) residential, commercial, light industrial and (b) industrial environment [1, 2].

In order to verify the electromagnetic compatibility of the plasma reactor installation it is necessary to carry out tests in accordance with the regulations of the EMC Directive and harmonised standards. Disturbances from any plasma oscillating source including fluorescent lamps, discharge tubes, and plasma tubes used in radar modules, as well as electron beam and arc welding can affect the electromagnetic environment [5–11]. Internal electromagnetic disturbances as well as near and far field components are derived and plotted [12]. Studies on plasma-related electromagnetic emissions and arc discharge are carried out in many aspects of physics and human interactions [13, 14].

According to the author, the plasma reactor power supply system, the working and ignition path, the discharge chamber, the gas feed system, together with the controls, are an example of a stationary installation that should be tested with a view to ensuring its proper functioning on the European market. According to the Directive [1], a fixed installation means a particular combination of several types of equipment and, where applicable, other devices, which are assembled, installed and intended to be used permanently at a predefined location. Therefore, the measurements of the plasma reactor installation were made at the place of its fixed installation, i.e., in the laboratory of the Department of Electrical Engineering and Electrotechnologies.

The presentation of the full compatibility analysis of the installation makes for an extensive publication, therefore the article only deals with the analysis of electromagnetic emissions. Demonstration of compliance will be based on conformity with the requirements and limits specified in the general standard International Electrotechnical Commission (IEC) 61000-6-4 [4].

2. GlidArc Plasma Reactor

Plasma reactors are technological devices that convert working gas into plasma by using electricity. The source of the plasma is an electric arc in the gas. The formation of an arc discharge is connected with the flow of current in the gas [5, 15–20].
Arc discharges are a non-linear and asymmetrical load for the supply system. Dynamically changing transient and short-circuit phenomena of the plasma producing discharges are the source of electromagnetic disturbances [2,3,21,22]. Electric arc discharge is related to the flowing current in the gas. The discharge depends on ionisation processes and its character determines the value of current flowing between electrodes. The voltage applied to the electrodes is also important.

One of the types of plasma reactors is a reactor with arc discharge gliding along electrodes under the technological name GlidArc. Figure 2 presents the installation of a three-phase GlidArc plasma reactor tested in the Department’s laboratory. Reactors of this type are used mainly in the neutralisation of toxic gases, such as SOx and NOx or in other technologies [17,19–28]. The quasi-arc discharge created in them is a source of non-thermal plasma filling part of the discharge chamber space. The source of plasma and the method of energy supply to it is the forced flow of electric current in gas in the form of an electric arc [15,16,18].

![Figure 2. Laboratory installation of a 3-phase GlidArc plasma reactor.](image)

The main feature of GlidArc reactors is the ability to generate non-thermal plasma directly in the contaminated gas, at atmospheric pressure and in the conditions in which the exhaust gases are emitted into the atmosphere. The idea of operating a reactor with a so-called gliding discharge is as follows. The treated gas is introduced axially, at a certain speed (volume flow), between the working electrodes. The device under test consists of three knife-shaped working electrodes, after which, under the influence of forced gas flow and electrodynamic forces, an expansive electrical discharge “glides”. The non-thermal plasma generated in this way fills a significant part of the discharge chamber space [5,15,18]. The voltage value on the electrodes needed to ignite the arc is 1–20 kV, but to sustain it the voltage is many times lower. The arc discharge begins in the place where the distance between the electrodes is the smallest (several millimeters).

The plasma of the gliding arc discharge, like other arc discharges, can be generated at DC, AC and pulse voltages. Industrial plasma reactors with gliding arc discharge are constructed as two-, three- and multi-electrodes and often have an additional ignition electrode [2,3,5,15,16]. The development of an arc discharge and its duration depends on several factors: the chemical composition of the gas, the temperature in the discharge chamber, the electrical parameters of the power supply system and the dimensions and geometry of the electrodes. An important element of the power supply is therefore the system of working electrodes.

The power supply of the three-phase plasma reactor used in the tests (Figure 2) is a system consisting of three single-phase transformers shown in the photograph. The transformers are connected to a star-star three-phase system with a neutral conductor. These transformers provide a maximum
sinusoidal power supply of 1.6 kV. This voltage does not guarantee arc ignition. Therefore, the reactor has ignition electrodes powered by a high voltage circuit—10 kV from ignition transformer – model Resinblock 2000 (F.A.R.T. SRL, PREGANZIOL, Italia)). The main power supply is regulated by the autotransformer – model HGT 400/8 (Metrel d.d., Horjul, Slovenia), the ignition system is regulated by 1-phase autotransformer – model SRV-5 CAP: 500VA (Chuan Hsin Electric Works Ltd., Taipei, Taiwan). A constant flow of air is introduced into the chamber from an oil-free compressor –model JWA-30 (Magnum Industrial, UK).

The ignition of the discharge on the working electrodes of a plasma reactor, analysed in this article, is initiated by an electric spark occurring between the ignition electrode and one of the three working electrodes. The spark discharges, depending on the electrodes distance and gas pressure, occur in the air at a voltage of 30 kV. The distance between the electrodes in the ignition zone is adjusted to (0.3–0.5) cm, what means the ignition voltage for air as a processing gas is equal to approximately (9–15) kV.

3. Test Stand

Electromagnetic emission testing requires an appropriate procedure and professional measurement equipment. The tests consist of two parts. The first part is the analysis of radiated interference emitted by the reactor installation, and the second part analyses the conducted interference measured in the power supply and ignition system of the reactor.

The measurement of radiated disturbances requires that the equipment under test is located in a separate area free from external interference during measurements. The measurements were taken in March 2020, when the university was closed due to an epidemiological emergency (coronavirus COVID-19). This reduced the external interference because all laboratories in the building were shut down. There were no additional disturbances in the background.

Radiation interference from the plasma reactor was investigated at a distance of 3 m from the installation. The 30 MHz–3 GHz frequency band was analysed. Legal requirements define the band only up to 1 GHz, but the band was increased to 3 GHz. This is because when the reactor is working, the Wi-Fi is not working properly. The measuring system consisted of an interference meter and three measuring antennas.

An interference meter is a measuring interference receiver (EMI test receiver). It uses model ESCI3 (Rohde&Schwarz GmbH & Co KG, Munich, Germany), which is compliant with standard CISPR 16 (Comité International Spécial des Perturbations Radioélectriques) [29]. The EMI test receiver is an indispensable apparatus in quantifying the magnitude of radio and conducted interferences emitted from that installation. That meter is also used to determine apertures compliant with national and international EMC standards. Antennas are used for measurements: HK116 Biconical Antenna (30–300 MHz), HL223 Log-Periodic Antenna (0.3–1 GHz) and HP906 Double-Ridged Waveguide Horn Antenna (1–3 GHz), all antennas are products of the Rohde&Schwarz GmbH & Co KG, Munich, Germany. These broadband antennas are used to measure radiated electromagnetic fields with an error of not more than ±3 dB. The measurement method and structure of the measuring station itself are based on the CISPR 16 [30] standard and the idea is presented in Figure 3. Sampling ranges have been set according to the standard. The tests have been done for two antenna polarisations—horizontal and vertical.

The second part of the tests concerns the measurement of conducted disturbances. The reactor installation does not have electronic control or data systems, so the tests of conducted electromagnetic interference are limited to the analysis of the power supply circuits. The elimination of additional (control) devices is a good idea here. This is the author’s new approach. It is related to the fact that the additional devices introduce some couplings and change the propagation of interference in the installation. The reactor has two circuits; the operating circuit and the ignition circuit, so two measuring systems are used.

Conducted disturbances were measured in the circuit of the reactor, ranging from 150 kHz to 30 MHz. The main elements of the measurement system are the EMI receiver and a special additional
device—LISN (Line Impedance Stabilisation Network), working as an artificial network. Figure 4 shows the measuring system. An ESC13 Rohde–Schwarz was used in all tests as an EMI receiver. A line impedance stabilisation network (LISN) is a device used in the conducted radio-frequency emission, as specified in various electromagnetic compatibility (EMC)/EMI test standards. A LISN is used to measure conducted emissions on power lines. It draws power from the ordinary wall outlet and feeds this to the equipment under test (reactor installations). Any disturbances generated by the reactor are separated by the LISN and fed to the EMI receiver for measurement.

![Measuring system for testing radiated emissions.](image1)

**Figure 3.** Measuring system for testing radiated emissions.

In the power circuit of the working electrodes a three-phase LISN (model SMZ-6/50, INCO Warszawa, Poland) was used. By switching successive measuring points in the artificial network, disturbances in phases L1, L2 and L3 were investigated. A single-phase LISN (model NNB41 LISN, Schaffner EMV AG, Luterbach, Switzerland) was switched on in the circuit supplying the ignition electrodes. The measurements were made on the L1 and N wires.

The measurements were carried out on a stand with grounded equipotential planes visible in Figure 2. This is another change compared to the author’s pilot studies conducted earlier [2,3,21].

![Measuring system for testing conducted emissions.](image2)

**Figure 4.** Measuring system for testing conducted emissions.
The measurements were carried out at the bandwidth of 120 kHz, step size of 40 kHz and measurement time of 10 ms.

All measurements (radiated and conducted) were made using a maximum value detector and an average value detector.

4. Results

Figures 5–8 show the measured electromagnetic interference generated by the GlidArc reactor installation. The tests of electromagnetic emission were carried out at a constant flow of gas volume (1000 dm³/h). The value of operating currents on the primary side of the transformer ranged between 5 A and 7 A, the value of primary voltage was 150 V.

![Figure 5. Measurement results—radiated emission, horizontal polarisation.](image1)
![Figure 6. Measurement results—radiated emission, vertical polarisation.](image2)
disturbances in the phase and neutral cables that supply the ignition system. Figure 8 shows the levels of conducted disturbances in the three phase wires supplying the operating electrodes of the reactor. All conduction disturbances were measured with the average detector. Here too, the graphs show the red limit of IEC 61000-6-4.

Figure 7. Conducted emissions—ignition system.

Figure 8. Measurement results—levels of conducted disturbances in the three-phase wires supplying the operating electrodes of the reactor.

The diagrams in Figures 5 and 6 show the measurement values of the electromagnetic field strength. The measurements were taken from three sides of the stand, and the article contains the results of the largest emission. In the beginning, the electromagnetic background (green curve) was measured with the average detector, when the reactor installation was switched off. External sources such as radio, television (TV), Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), wireless networking technologies (Wi-Fi), Long Term Evolution (LTE) transmitters were observed. In the next step, emission measurements were made when the reactor installation was switched on. The results are from two detectors, maximum (turquoise) and average (orange). Measurements were taken for two polarisations—the horizontal (shown in Figure 5) and vertical polarisation (shown in Figure 6). The graphs show the red limit of IEC 61000-6-4 Generic standards—emission standard for industrial environments.
The next part of the tests concerned the measurement of conducted disturbances in the wires supplying the main circuit and the ignition circuit. Figure 7 shows the levels of conducted disturbances in the phase and neutral cables that supply the ignition system. Figure 8 shows the levels of conducted disturbances in the three phase wires supplying the operating electrodes of the reactor. All conduction disturbances were measured with the average detector. Here too, the graphs show the red limit of IEC 61000-6-4.

5. Discussion

The reactor is built for research tasks. The working gases during operation can be nitrogen, helium, argon, oxygen and air. For the purpose of this publication, tests with air are presented. In the case of lack of or insignificant flow, the arc discharge space is uniform, and more stable in terms of current flow, unfortunately it overheats the electrodes locally. At higher air mixture flow velocities, the discharge is ejected into the further inter-electrode space and it is rapidly interrupted while gliding along the electrodes. This does not provide a stable plasma throughout the space and shows a high level of electromagnetic disturbances. This is particularly evident in radiated disturbances, as can be seen in the Figures 5 and 6. These dynamic interruptions can only identify a fast maximum detector, which is clearly visible on both characteristics (Figures 5 and 6) as the highest interference curve. The average detector also indicates higher levels of electromagnetic emissions than the background, but the levels obtained are acceptable. The use of classic shielding measures will maintain the disturbance within acceptable levels. Extending the measuring band to 3 GHz is also important here. For the first time there is information on how much interference such an installation with arc discharge introduces into the environment. This is important because we have more and more electronic equipment that works in this band and the reactor can interfere with their operation.

The results of the conductive disorder test are unambiguous. The nature of the disturbances has broadband characteristics. The non-linear and asymmetric loads that characterise the plasma reactor translate into the random character of emission distribution. The measurement results obtained for air show that the limit values are significantly exceeded.

Thus, as shown by the emission tests, the plasma reactor installation does not meet the emission requirements, which disqualifies this installation from production, sale and further operation.

Local function extremes are also interesting at these levels of interference. According to the author, they indicate the existence of the phenomenon of resonances occurring in the capacitance and inductance circuit. Their thorough analysis can be useful in improving models of arc discharge and plasma, e.g., modelling of the gliding arc behaviour of a plasma torch or plasma reactor operating with air under low current and high voltage conditions [31–33].

6. Conclusions

The operation of Glidarc plasma installation was analysed from the EMC-radiated and conducted emission point of view. For safety and legal reasons it is necessary to monitor the electromagnetic compatibility of plasma reactors.

Arc discharges introduce radiated disturbances into the environment and caused disturbances in the power supply system. When a reactor in the laboratory is switched on, it interferes with other equipment in the local environment. This is particularly visible in computer monitors, electronics controlling the reactor systems, lack of correct Wi-Fi transmission in the nearest space, and in the transmission of GSM calls. The results of professional measurements confirm that the permissible levels of electromagnetic emissions are exceeded. The author’s research and literature studies indicate that the interference is in many types of reactors and installations with arc discharge [2,3,5,11,12,15]. These are high emission levels, for the measured installation exceeding 20 dB.

Very large conductive disturbances were measured. They are so large that their impact on energy quality and reliability of the power supply system has to be determined. A poorly functioning power supply can cause unstable arc and plasma.
Understanding the physical processes responsible for the radiated and conducted emission makes it possible to design anti-interference components. This situation forces further testing. The tests must be carried out at many levels. Interference levels must be determined in many different reactor operating configurations, at different gas flow rates, different supply voltages, different electrode geometries, different ignition systems.

On the other hand, work is necessary to improve compatibility. Thus, the principles of filtration and shielding of such installations must be defined. High levels of interference indicate the need to design filtration systems with chokes that have amorphous or nanocrystalline core material. Such filters have high attenuation.

**Funding:** This research was funded by the Lublin University of Technology.

**Conflicts of Interest:** The author declares no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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