THE NUMERICAL ANALYSIS OF THE INTEGRATED
SUPPLY SYSTEM OF GLIDARC PLASMA REACTOR

L. Jaroszyński, H. D. Stryczewska
l.jaroszynski@pollub.pl, h.styczewska@pollub.pl
Institute of Electrical Engineering and Electrotechnologies
Technical University of Lublin, ul. Nadbystrzycka 38A, 20-618 Lublin, Poland

Key words: gliding arc, supply system, plasma reactor, modified Mayr's arc model

1. INTRODUCTION

Non-thermal plasma reactors represent emerging technology of air pollution control and plasma chemistry that permits to treat large volumes of gas containing dilute concentrations of reagents. The GlidArc gas processing is able to enhance initiation of chemical reactions in gas mixtures at low temperatures, it increases the reaction effectiveness and drives the reactions towards optimal conversion conditions. It can be utilised for gas processing which is structurally modified to become a completely different end product. An instance of this is the producing of Synthesis Gas (CO + H₂) from any hydrocarbon feed stock in which various hydrocarbons are Plasma-Steam-Reformed to carbon monoxide and hydrogen at a relatively low temperature and low pressure compared to some conventional processes, and at low cost [3].

2. GLIDARC I PLASMA REACTOR

In the GlidArc type I plasma reactor the non-thermal plasma is produced by electric arc discharges gliding throughout reactor electrodes due to forced gas flow. The basic idea of GlidArc I reactor is presented in Fig. 1.

Two or more knife-shaped working electrodes are put into the processing chamber to which the treated gas is injected. An additional central striking electrode is applied for ignition of the discharge. After ignition the discharge is gliding through electrodes together with fast moving gas. The electrode distance grows, the arc discharge becomes longer, the arc voltage becomes higher and in some place of electrodes (the zone of arc extinction) goes out.

Time of the single cycle of the reactor operation (from the ignition to the extinction of the arc discharge) depends on electrodes shape and dimensions, gas parameters, its velocity and temperature and can be equal to several periods of 50 Hz supply network voltage. In the ignition zone the discharge has the arc nature but during rapid displacing along electrodes by flowing gas becomes similar in nature to glow discharge. Such a discharge is the source of high-pressure non-equilibrium plasma that is applied, for instance, in processes of air cleaning from dangerous for environment gaseous pollutants.

3. INTEGRATED SUPPLY SYSTEM

The general schematic diagram of the integrated supply system is shown in Fig. 2. It consists of three single-phase working transformers TX1, TX2, TX3 and an igniting transformer TX4. Working transformers supply electric energy to the discharge. They provide voltage of about 1.5 kV and frequency of 50 Hz. The third harmonic has the biggest contribution in the current of the primary winding of the igniting transformer. This harmonic is generated by non-linear magnetic cores of working transformers. That is why the striking voltage amplitude is about 10 kV and the frequency is 150 Hz. This system is very simple and reliable. It also improves the efficiency of electrical ignition [1].

Fig. 2. Schematic diagram of the integrated supply circuit of GlidArc I plasma reactor (patents: T. Janowski, H. D. Stryczewska, PL 172170 and PL 172152, 1997)

Fig. 3. Simulation circuit of the integrated supply system of GlidArc plasma reactor

The photograph of the integrated supply system model is presented in Fig. 4.
Basic parameters of this supply system:

- working electrode voltage in no-load state $U_{20}=1.7$ kV,
- working electrode operating current $I_2=1$ A,
- number of working electrodes $w=3$,
- striking voltage in no-load state $U_{Z0}=10$ kV,
- short-circuit current of the igniting electrode $I_{Z2}=20$ mA.

4. NUMERICAL SIMULATION

The numerical simulation of the integrated supply system for the GlidArc plasma reactor was carried out utilising a general circuit analysis package MicroSim PSpice. Preparation of non-linear component models has been the most difficult part of this task. Fortunately, Jiles-Atherton (JA) mathematical model of non-linear magnetic core is included in the modern PSpice software. This model assumes that the hysteresis effect can be explained on the basis that the total magnetic magnetisation $H_i$ (1) of ferromagnetic core depends on reversible and irreversible energy loses during domain wall motions.

$$\frac{dH_i}{dH} = \frac{1}{1 + C} \cdot \frac{(H_{i_a} - H_i)}{K} + \frac{C}{1 + C} \cdot \frac{dH_{i_a}}{dH}$$

(1)

where:

- $H_{i_a} = H_{i_s} \cdot \frac{H}{|H| + A}$ - anhysteric magnetisation, $H$ - magnetic field strength,
- $A$ - thermal energy parameter, $C$ - domain flexing parameter, $K$ - domain anisotropy parameter, $H_{i_s}$ - magnetisation saturation.

This impedance to motion and flexing due to the differential field exhibits all of the main properties of real, non-linear magnetic materials, such as: the initial magnetisation curve (initial permeability), saturation of magnetisation, coercivity, remanence and hysteresis losses. Unfortunately, this approach doesn’t take into account the influence of frequency and eddy current loses.

Jiles-Atherton model parameters can be derived from experimental results (first quadrant of B-H characteristic) using PARTS subprogram of PSpice. Unfortunately this tool gives sometimes false results on account of week numerical solution convergence.
That is why the additional Pascal program has been prepared which permits calculation of JA model parameters. The screen dump during operation of this software is presented in Fig. 5.

Fig. 5. Computer display dump during calculation of JA model parameters for the transformer core

In this work the attempt to use "black box" electric arc model has been done for the numerical simulation of plasma reactor. Arc model has been prepared using modified Mayr's equation of non-linear conductance (2) and it has been extended with ignition subcircuit [2].

\[
g(t) = g_0 \cdot e^{-\frac{1}{\tau(g)} \left( \frac{u^2(t) \cdot i(t)}{a(t) \cdot i(t) + c(t) \cdot u(t)} \right)}
\]

where:

- \( g(t) \) - electric discharge conductance;
- \( g_0 \) - initial value of the discharge conductance;
- \( \tau(g) \) - discharge time constant;
- \( u(t), i(t) \) - discharge voltage and current;
- \( a(t), c(t) \) - functions describing power taken from the electric discharge.

Simulation circuit of the integrated supply system of GlidArc plasma reactor is shown in Fig. 3. Additional capacitor \( C_Z \) permits control of striking voltage level in certain range. The load of the supply system has been simulated as a combination of three discharge models mentioned above. The striking voltage has been initiating every operation cycle of GlidArc reactor. However, the igniting discharge evolution hasn't been investigated. This simplification is allowable because of high value of short circuit impedance of striking transformer.

5. SELECTED RESULTS

During numerical simulation certain electric waveforms of the supply system have been computed, starting from no-load state and the resistive load. Selected results are shown in Fig. 6, Fig. 7, Fig. 8 and Table 1. Several electric waveforms in non-linear load (GlidArc) also have been computed. Picked waveforms are presented in Fig. 9. Numerically achieved waveforms demonstrate good compliance with laboratory results.
Laboratory test

Fig. 6. Primary winding current of working transformer in no-load state (0.5A/div)

Laboratory test

Computer simulation

Fig. 7. Working electrode voltage (upper waveforms, 2kV/div) and striking voltage (lower waveform, 10kV/div) in no-load state

Table 1. Selected electrical parameters in no-load state (TZ applies to striking transformer)

<table>
<thead>
<tr>
<th>$U_1$</th>
<th>$I_1$</th>
<th>$P_1$</th>
<th>$I_N$</th>
<th>$U_{1TZ}$</th>
<th>$U_2$</th>
<th>$U_{2TZ}$</th>
<th>$U_1$</th>
<th>$I_1$</th>
<th>$P_1$</th>
<th>$I_N$</th>
<th>$U_{1TZ}$</th>
<th>$U_2$</th>
<th>$U_{2TZ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>A</td>
<td>W</td>
<td>A</td>
<td>V</td>
<td>V</td>
<td>V</td>
<td>V</td>
<td>A</td>
<td>W</td>
<td>A</td>
<td>V</td>
<td>V</td>
<td>V</td>
</tr>
<tr>
<td>380</td>
<td>0.42</td>
<td>99</td>
<td>0.25</td>
<td>143</td>
<td>1568</td>
<td>6700</td>
<td>380</td>
<td>0.47</td>
<td>65</td>
<td>0.26</td>
<td>141</td>
<td>1635</td>
<td>8900</td>
</tr>
</tbody>
</table>

Fig. 8. Load characteristic of the supply system: 1, 2, 3 – experimental results for different working transformer distances, 4 – numerical simulation results
Laboratory test

Computer simulation

Fig. 9. Voltage (upper waveforms, 2kV/div) and current (lower waveform, 5A/div) of electric arc load ($T_{Cn}$ - GlidArc operation cycles, $T_{Pn}$ - zero current periods)

6. CONCLUSION

- The numerical analysis of the supply system of GlidArc plasma reactor can speed up and simplify the design process however it requires certain mathematical models of the non-linear components: electric arc discharge and magnetic cores.
- Standard PSpice package can be comfortably extended using Analogue Behavioural Modelling (ABM) blocks for simulation of user defined components.
- The extension of Mayr's and Cassie's switching arc equations is possible, therefore these equations can be applied in analysis of operation of the GlidArc plasma reactor and the integrated supply system.
- The numerical analysis using simplified magnetic core model and electric discharge model allows to evaluate supply system parameters, this analysis can be an important element in the verification of supply system design.

7. REFERENCES