Consistent simulation of capacitive radio-frequency discharges and external matching networks

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Abstract

External matching networks are crucial and necessary for operating capacitively coupled plasmas in order to maximize the absorbed power. Experiments show that external circuits in general heavily interact with the plasma in a nonlinear way. This interaction has to be taken into account in order to be able to design suitable networks, e.g., for plasma processing systems. For a complete understanding of the underlying physics of this coupling, a nonlinear simulation approach which considers both the plasma and the circuit dynamics can provide useful insights. In this work, the coupling of an equivalent circuit plasma model and an external electric circuit composed of lumped elements is discussed. The plasma model itself is self-consistent in the sense that the plasma density and the electron temperature is calculated from the absorbed power based on a global plasma chemistry model. The approach encompasses all elements present in plasma systems, i.e., the discharge itself, the matching network, the power generator as well as stray loss elements. While the main result of this work is the conceptual approach itself, at the example of a single-frequency capacitively coupled discharge its applicability is demonstrated. It is shown that it provides an effective and efficient way to analyze and understand the nonlinear dynamics of plasma systems including the external circuit and, furthermore, may be applied to synthesize optimal matching networks.

Keywords: simulation, capacitively coupled plasma, impedance matching, global model, SPICE, circuit simulation

1. Introduction

Capacitively coupled plasmas (CCPs) operated at radio frequencies (RFs) are powered by generators that are connected to the driven electrode via an external electrical circuit \cite{1, 2}. These circuits depend on the specific setup and may among other elements include power lines, matching networks, frequency filters. Since the plasma is typically a nonlinear load, its interaction with the external circuit is not easily predictable. Especially at low pressures $p < 10$ Pa, harmonics in the plasma current at the plasma series resonance can have a strong influence on the plasma characteristics \cite{3–9}. It has been observed by several researchers in the field that these harmonics interact heavily with the external circuit connected to the driven discharge electrode \cite{7, 9–12}, e.g., reacting to simple changes such as a varied cable length \cite{7}. Yamazawa \textit{et al} demonstrated that this interaction can be used to influence the electron density and its homogeneity by changing the composition of the harmonics with an LC unit parallel to the plasma \cite{13, 14}. In many plasma applications, matching networks are an essential part in order to maximize the absorbed power in the plasma and avoid reflection \cite{1, 2}. These networks are almost always lossy, which impairs the efficiency of the whole system. Various authors have studied these losses in experimental setups \cite{15–18}. To investigate the influence of plasma and network parameters on the efficiency, a simulation can provide additional insights. Furthermore, analytic predictions of the nonlinear effects are hard
to obtain, whereby an effective numerical simulation that takes both plasma and external circuit into account may enlighten the underlying dynamics. Certain assumptions about the plasma states are, however, often necessary. Verboncoeur et al proposed a method for coupling external circuits to a particle in cell (PIC) simulation via conservation of charge [19]. The external circuit is incorporated by setting up the differential equations following Kirchhoff’s circuit laws and solving them numerically simultaneously with the PIC simulation. Raut and Kushner analyzed the plasma circuit interaction by coupling a lumped circuit to a plasma simulated with HPBM [10]. They observed that the specific design of a matching network has a significant influence on the plasma and, therefore, the whole system of interest.

In this work, we propose a simulation method in which the plasma itself is modeled by a nonlinear equivalent circuit consistently coupled to a global chemistry model. Therefore, the problem reduces to a circuit simulation for which several solution tools are available. These tools, one of which is SPICE, solve the system of differential equations using a netlist of the circuit [20]. Here, we make use of the open-source software ngSPICE [21]. The differential equations, hence, do not need to be set up and solved ‘by hand’, which is especially cumbersome for large circuits. As aforementioned, the proposed simulation algorithm self-consistently calculates the electron temperature and the plasma density based on the absorbed power and parameters of the discharge. The functionality of the proposed method is demonstrated by simulating a simple generator with an L-type impedance matching network attached to the plasma model (including losses in the network and the reactor chamber).

2. Plasma model and simulation algorithm

In order to describe efficiently the nonlinear dynamics of RF plasma systems on the high-frequency timescale and to understand the interaction between the plasma and the external network, a lumped element circuit model for the plasma is established. In this work, the model is based on considerations introduced and discussed in [4, 6, 8, 22]. It additionally allows to consistently calculate the electron temperature and density from particle and energy conservation in the system [1].

The plasma is divided into the plasma bulk and the two sheaths: one sheath at the driven electrode and the other at the grounded electrode and reactor chamber wall. A generalized Ohm’s law based on the momentum equation for electrons of the form

$$ \frac{\partial \tilde{n}}{\partial t} = \frac{e^2 n}{m_e} \tilde{E} - \nu_{\text{eff}} \tilde{j} $$  

(1)

is used to model the bulk on the RF timescale. \( \tilde{j} \) is the current density, \( \tilde{E} \) the electric field, \( n \) the plasma density, and \( m_e \) the electron mass. The effective collision frequency \( \nu_{\text{eff}} = \nu_m + \tilde{v}_e / \bar{u}_e \) accounts for both ohmic heating by incorporating the momentum transfer collision frequency \( \nu_m \) and stochastic heating in form of the second term. Therein, \( \bar{u}_e = (8 k_B T_e / \pi m_e)^{1/2} \) is the mean thermal speed, \( T_e \) the electron temperature, \( \nu_m \) is the bulk length, and \( k_B \) is the Boltzmann constant. Assuming a homogeneous cylindrical discharge, integration over the electrode area \( A_E \) and the bulk length \( l_B \) respectively leads to a scalar version of equation (1). This can be written in the form \( V_{\text{bulk}} = R_{\text{pl}} i_{\text{bulk}} + L_{\text{pl}} \frac{d}{dt} i_{\text{bulk}} \), with \( V_{\text{bulk}} \) the voltage dropping over the bulk and \( i_{\text{bulk}} \) the current flowing through the bulk and, therefore, through the whole discharge. Recapitulatory, the bulk is modeled by an inductor \( L_{\text{pl}} = l_B m_e / \epsilon \nu_{\text{eff}} A_E \) and a resistor \( R_{\text{pl}} = \nu_{\text{eff}} L_{\text{pl}} \).

The sheaths of the plasma are modeled by a capacitive diode consisting of three parallel elements. Due to their high inertia, the ion flux onto the surface is assumed constant and is accordingly modeled as a constant ion current source \( I_{i,1} = A_E \bar{u}_i m_i \), with the Bohm velocity \( \nu_B = \sqrt{k_B T_e / m_i} \) and the ion mass \( m_i \). The electrons have a much lower mass \( m_e \) and thus depend on the time-varying sheath voltage \( V_{\text{S}} \). The electron current is then \( I_{e,1} = A_E \bar{u}_e m_e \exp(-e V_{\text{S},1} / k_BT_e) \), assuming a Maxwellian electron energy distribution. Lastly, the sheath capacitance is modeled as a nonlinear capacitor \( C_{\text{S}} = (e n e_0 A_e^2 / V_{\text{S},1})^{1/2} \). The nonlinearity itself depends on the applied sheath model. In this work a matrix sheet model [1] is used. \( I_{i,1}, I_{e,1} \) and \( C_{\text{S},1} \) are the values describing the sheath in front of the driven electrode. The values for the grounded electrode sheath are obtained by exchanging \( A_E \) with \( A_G \), consequently, \( I_{i,2} = A_G \nu_B m_i \), \( I_{e,2} = A_G \bar{u}_e m_e \exp(-e V_{\text{S},2} / k_BT_e) \) and \( C_{\text{S},2} = (e n e_0 A_e^2 / V_{\text{S},2})^{1/2} \). The system of differential equations for the plasma model to be solved then amounts to

$$ \frac{d V_{\text{S},1}}{dt} = -C_{\text{S},1}^{-1} (I_{\text{pl}} + I_{i,1} - I_{e,1}), \quad (2) $$

$$ \frac{d V_{\text{S},2}}{dt} = -C_{\text{S},2}^{-1} (-I_{\text{pl}} + I_{i,2} - I_{e,2}), \quad (3) $$

$$ \frac{d I_{\text{pl}}}{dt} = L_{\text{pl}}^{-1} (V_{\text{pl}} + V_{\text{S},1} - V_{\text{S},2}) - \nu_{\text{eff}} I_{\text{pl}}, \quad (4) $$

with \( V_{\text{pl}} \) being the voltage dropping over the whole discharge. This system of equations can be described by an equivalent circuit model, which is depicted on the very right-hand side of figure 1.

Since this model consists only of circuit elements, arbitrary networks using sources, resistors, capacitors, inductors and so on can be attached to the electrode and, following
Kirchhoff’s laws, the resulting differential equations can be solved. However, since the plasma density \( n \) depends on the absorbed power \( P_{\text{abs}} \), which in return depends on the attached electric circuit, the model needs to be extended to catch this dependency. Following the argument of Lieberman and Lichtenberg [1], the energy lost per electron–ion pair created depends on the energy lost due to collisions and due to particles leaving the system. For the former, an equation \( \varepsilon_c = (K_{\text{iz}} \varepsilon_{\text{iz}} + K_{\text{ex}} \varepsilon_{\text{ex}} + K_{\text{el}} \varepsilon_{\text{el}}) / K_{\text{iz}} \) can be derived. The energy lost due to collisions \( \varepsilon_c \) depends on the rate constants \( K_{\text{iz}} \), \( K_{\text{ex}} \), and \( K_{\text{el}} \) for ionization, excitation and elastic collisions as well as the respective energies \( \varepsilon_{\text{iz}}, \varepsilon_{\text{ex}} \) and \( \varepsilon_{\text{el}} \). The values of the rate constants depend on the chosen background gas and on the electron temperature. In this work, approximation functions provided by Gudmundsson for an argon discharge are used [23]. The energy lost by particles leaving the system needs to be accounted for, for each charged species. For electrons following a Maxwellian distribution this energy can be assumed to be \( \varepsilon_e = 2k_B T_e \). Ions have an initial energy of \( k_B T_e / 2 \) at the Bohm point and are then accelerated following the mean sheath voltage \( V_{\text{s}} \) resulting in \( \varepsilon_i = e V_{\text{s}} + k_B T_e / 2 \). Accounting for the different sheaths at the driven and grounded electrode and the electrode sizes respectively, the total ion energy lost results in \( \varepsilon_i = f_{\text{iz}} e V_{\text{s},1} + f_{\text{ex}} e V_{\text{s},2} + k_B T_e / 2 \) with the weighting factors \( f_{\text{iz}} = A_{\text{iz}} / (A_{\text{iz}} + A_{\text{ex}} + A_{\text{el}}) \) and \( f_{\text{ex}} = A_{\text{ex}} / (A_{\text{iz}} + A_{\text{ex}} + A_{\text{el}}) \). The absorbed power can then be calculated taking all created electron-ion pairs in the plasma volume \( V_p = A_E I_0 \) into account, which results in

\[
P_{\text{abs}} = n V_p n_e K_{\text{iz}} (\varepsilon_e + \varepsilon_i + f_{\text{iz}} \varepsilon_{\text{iz}} + f_{\text{ex}} \varepsilon_{\text{ex}} + f_{\text{el}} \varepsilon_{\text{el}}),
\]

with the neutral gas density \( n_g \). Since the total number of electrons and ions created needs to be equal to the number of particles leaving the system, a condition for particle conservation

\[
V_p n_g K_{\text{iz}} = u_0 A
\]

can be established with the total area \( A = A_{\text{iz}} + A_{\text{ex}} + A_{\text{el}} \) and \( V_p \) are geometrical values that depend on the actual setup of the plasma. Again, assuming a cylindrical discharge, both values can be calculated once the electrode area \( A_{\text{iz}} \) is known. It is in this case important to keep in mind that \( A_{\text{ex}} \) is not necessarily the grounded area of the reactor, but rather the sheath size in front of the grounded reactor parts and, therefore, typically smaller. Once geometrical assumptions about the discharge are made, equation (6) can be used to calculate the electron temperature with both \( u_0 \) and \( K_{\text{iz}} \) being functions of \( T_e \). It is also possible to do it the other way around, i.e., to calculate \( A \) and \( V_p \) from the electron temperature, which might be known for a specific discharge from measurements.

In the actual simulation algorithm depicted in figure 2, equation (6) is evaluated once at the beginning of the simulation in order to set \( T_e \). It is assumed that the electron temperature and the geometrical parameters do not vary with the absorbed power, i.e., the plasma does not vary in size. In order to perform a transient simulation of the whole system of interest, all elements of the circuit have to be assigned specific values. In other words, the external lumped element circuit needs to be set up (e.g., generator, matching network, loss elements) and the elements of the plasma model need to be calculated. All values of the plasma elements depend on \( T_e \) — which is already known at this point — and the plasma density for which a (reasonable) value is guessed. This leads to a network with completely determined elements. Especially for large networks it is highly advisable to not set up the differential equations for the whole network by hand, but rather make use of a circuit simulation software, for which several tools are available. Due to its flexibility, being open-source and providing shared libraries, we make use of the software ngSPICE, which is based on SPICE [20, 21].

A transient simulation of the circuit determines all currents and voltages at each branch and node. Therefore, the absorbed power of the plasma can be calculated from the voltage \( V_{\text{pl}} \) dropping over the plasma and the current \( I_{\text{pl}} \) flowing through it in the form \( P_{\text{abs}} = \frac{1}{2} I_{\text{pl}} V_{\text{pl}} \) (see figure 1). The averaged voltages across the sheaths are obtained from the simulation as well. Equation (5) is then used to calculate the plasma density from these values. Afterwards, using this new value of \( n \), the elements of the plasma model can be updated and the simulation can be performed again. This step is repeated until a steady state of \( n \) and \( P_{\text{abs}} \) is reached. At this point, for a specific circuit, consistent values of \( n, P_{\text{abs}}, I_{\text{pl}} \) and any other current, voltage or power of interest are obtained. Changes in the external circuit can be applied, which is the outer iteration loop of the algorithm (see figure 2), and the correct values of \( n \) and \( P_{\text{abs}} \) obtained again. In this work, changes to the network are employed in the impedance matching network until the load is matched to the generator. Another application of the proposed model for a multi frequency matching network can be found in a previous publication [24].

3. Results and discussion

A typical network commonly attached to an RF plasma discharge consists of a generator (to provide power) and a matching network (to insure that a maximum amount of this power actually reaches the plasma). Such a setup is simulated in this work as depicted in figure 1. Transmission lines are

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**Figure 2.** Flowchart of the algorithm of the simulation.
ignored in this setup, but can easily be added making use of models provided by ngSPICE [21]. The generator consists of a voltage source \( V_g = V_0 \cos(\omega t) \), with \( V_0 = 100 \, \text{V} \), \( \omega = 2 \pi \times 13.56 \, \text{MHz} \), and an internal resistor \( R_g = 50 \, \Omega \). The matching network is a typical L-type network with tunable capacitors \( C_{m1} \) and \( C_{m2} \) and a fixed inductor \( L_{m2} = 1500 \, \text{mH} \). Accumulated losses of the matching network are included in the form of a resistor \( R_m = 0.5 \, \Omega \). Stray effects that occur at the reactor chamber and supply lines are modeled in the form of a resistor \( R_{st} = 0.5 \, \Omega \) and a capacitor \( C_{st} = 200 \, \text{pF} \). All values of the loss elements are rough estimates and intrinsically depend on the setup of the chamber, the network and supply lines, and the specific choice of matching elements. In this work, generic but reasonable circuit element values are used to demonstrate the simulation principle. To simulate a specific setup, the losses and stray effects of the network can be measured [1, 18] and thus included in the simulation. Other sources of stray effects (e.g., in the matching network) are ignored in this work.

The discharge considered in the simulation has a driven electrode area \( A_g = 100 \, \text{cm}^2 \), a grounded area \( A_g = 300 \, \text{cm}^2 \) and a bulk length \( h_b = 5.7 \, \text{cm} \).

In the outer loop of the algorithm (accounting for changes in the external circuit), \( C_{m1} \) and \( C_{m2} \) are optimized in order to maximize the absorbed power of the load. This is done by performing a fast Fourier transform (FFT) of the transient load voltage \( V_L \) and current \( I_L \), and calculating the complex load impedance \( Z_L(\omega_k) = \mathcal{F}[V_L]/\mathcal{F}[I_L] \). At the excitation frequency \( \omega_i \) with \( k = 1 \), the matching conditions are \( \text{Re}[R_{eff}[C_{m1}] = \text{Re}[Z_L] \) and \( \text{Im}[Z_L] + \text{Im}[R_{eff}[C_{m1}] = j \omega_i L_{m2} + 1/j \omega_i C_{m2} \) [1]. \( C_{m1} \) and \( C_{m2} \) can be chosen to satisfy these equations. The simulation is repeated afterwards with these new values following the algorithm depicted in figure 2. Since changes in the matching network have a significant influence on the absorbed power in the load and, therefore, the plasma (which changes its elements and, accordingly, the impedance \( Z_L \), this step has to be repeated several times, until \( C_{m1} \) and \( C_{m2} \) reach a steady state. Typically, up to five iterations of changes in the matching network are required.

For the chosen setup two exemplary cases are simulated: I. a low pressure of \( p = 0.66 \, \text{Pa} \) for which a high number of nonlinearly generated harmonics are expected; II. a high pressure of \( p = 200 \, \text{Pa} \) with a presumably low harmonics content due to collisional damping.

### 3.1. Low pressure \( p = 0.66 \, \text{Pa} \)

For a pressure of \( p = 0.66 \, \text{Pa} \) and an argon background gas with a temperature \( T_g = 300 \, \text{K} \), the neutral gas density can be calculated to \( n_g = p/k_B T_g = 1.59 \times 10^{20} \, \text{m}^{-3} \). Using this value, equation (6) is taken to calculate an electron temperature of \( k_B T_e = 4.75 \, \text{eV} \).

A converged and matched steady state simulation is obtained for the values \( n = 1.25 \times 10^{20} \, \text{m}^{-3} \), \( C_{m2} = 175 \, \text{pF} \) and \( C_{m1} = 1550 \, \text{pF} \). The total load at \( \omega_i \), including the matching network, amounts to an impedance \( Z_{TL} = V_{TL}/I_{TL} = (50.01 - j 0.02) \, \Omega \), which is very close to \( R_{eff} = 50 \, \Omega \) and, therefore, close to perfect matching to the generator. This value can be improved by using more iterations in the algorithm and especially by choosing smaller timesteps and longer simulation periods in the transient simulation of the circuit performed by ngSPICE, which would increase the numerical accuracy.

The resulting transient values of the current \( I_{pl} \) and the voltage \( V_{pl} \) are plotted in figure 3. The voltage has an amplitude of about 360 V and an offset of –250 V, while being almost completely sinusoidal. The current on the other hand is composed of a variety of harmonics due to the nonlinearity of the plasma. It is particularly interesting to analyze the different harmonics at the various network nodes.

In figure 4, the amplitudes of the different currents in the system at the excitation frequency \( \omega_i \) obtained by a FFT are depicted. As expected, \( I_{rf} = 1 \, \text{A} \), which is the same result as \( I_{rf} = |V_{rf}/(R_{rf} + Z_{TL})| \) yields for a perfectly matched load. The current flowing in the plasma is with \( I_{pl} \approx 0.6 \, \text{A} \) much smaller than the currents \( I_{rf} \approx 6.7 \, \text{A}, I_{m2} \approx 6.6 \, \text{A} \) and \( I_{stray} \approx 6.1 \, \text{A} \) in the other branches.

These currents lead to powers absorbed at different locations in the system: in the plasma, in the matching network at \( R_{m2} \) in the stray line at \( R_{stray} \) and in the internal resistance \( R_{rf} \). Since the load is ideally matched, the amount of power dissipated in \( R_{rf} \) is 25 W, while the same amount of power is distributed over \( R_{m2}, R_{stray} \) and the plasma. This power distribution is plotted in figure 5. It can be seen that more than 80% of the power is dissipated in the loss elements and a little less than 20% is transmitted into the plasma. The system is consequently very inefficient for this specific setup. This is reasoned by the high circular current that arises in the path \( I_{L}, I_{m2} \) and \( I_{stray} \). The plasma model has an impedance at
the excitation frequency of $Z_{pl} = (29.65 - j658) \Omega$ with its parallel stray-path having an impedance of $Z_{stray} = (0.5 - j58.58) \Omega$. The high plasma impedance, especially its reactive part, is the reason for the low efficiency. The impedance values of the plasma are on the same order of magnitude as measurements performed by Andries et al [16].

Conclusively, most of the current flows through the reactor stray path and not through the plasma. While these results make this setup not suitable for industrial applications, it is generally in line with the powers measured by Godyak and Piejak [18], who report losses of ≈60% at low pressures, using a more complex plasma and matching setup.

The nonlinearly created harmonics in the current for which the plasma acts as a generator are another peculiarity. Leaving out the dominant current component at the fundamental excitation frequency, figure 6 presents the amplitudes of the different harmonics of the currents through the various branches of the system. The plasma generates a total current at $2\omega_t$ of about 0.15 A amplitude. There exist contributions up to the 12th harmonic with comparably small amplitudes of around 0.05 A. The stray current $I_{stray}$ is of roughly same amplitude, while the values for $I_1$ and $I_{m1}$ are much smaller. Only the second harmonic with $-0.02$ A is clearly distinguishable in the plot. In the generator current $I_{gf}$ even the second harmonic is almost completely suppressed. This effect can be understood by considering the position of the plasma in the network as a generator. In this case, the three branches with $C_{stray}$, $L_{m2}$ and $C_{ml}$ act as a (lossy) low-pass filter of third order with each branch suppressing high frequencies. This suppresses higher harmonics up to the point that non factually reach the ‘load’ (the RF source branch). This behavior is generally desirable since higher harmonics might otherwise create problems in the form of reactive power in the generator. It is important to note, however, that in this setup, even with a very nonlinear plasma, the power transfer is highly dominated by the excitation frequency, while the harmonics do not have a significant impact. This is mainly due to the fact that the voltage at the electrode is almost completely sinusoidal, thereby the plasma, while generating harmonics in the current, does not create power at the harmonic frequencies.

Stray effects occur in practice not in the form of a specified branch as assumed in the simulation, but distributed over the system, such as at the coaxial cable feed and at the driven electrode [1]. The further away from the electrode in the direction of the matching network a measurement of the current is performed, the less of the plasma-generated harmonics this current is expected to contain. Resultantly, a measurement of the plasma current, which is desired to include these harmonics, needs to be performed as close to the plasma as possible.

3.2. High pressure $p = 200$ Pa

With a pressure of $p = 200$ Pa and $T_e = 300$ K, the neutral gas density is calculated to $n_e = \rho/k_B T_e = 4.83 \times 10^{22}$ m$^{-3}$ and the electron temperature following equation (6) is $k_B T_e = 1.87$ eV.

The simulation converges at a perfectly matched steady state for the values $n = 8.75 \times 10^{23}$ m$^{-3}$, $C_{m2} = 176$ pF and $C_{ml} = 545$ pF. The total load at $\omega_t$ amounts to an impedance $Z_{TL} = V_{TL}/I_{gf} = (50.04 - j0.08) \Omega$, which, again, is very close to $R_{ef} = 50 \Omega$.

In figure 7 the plasma-voltage and current over two periods is depicted. It is clearly visible that the current contains way less harmonics compared to the low pressure case.
and is conclusively closer to a sinusoidal shape. The voltage is almost completely sinusoidal.

As nonlinearities are highly damped, an analysis of this case is mostly of interest only for the excitation frequency. The amplitudes of the currents in different paths of the system are presented for this frequency in figure 8. Again, the current in the paths of $I_L$, $I_m$, and $I_{stray}$ is larger than $I_{pl}$. Compared to the low pressure case in figure 4, this variation is much smaller though. Conclusively, the system is much more efficient in transferring power into the plasma, as can be seen in figure 9. Less than 10% of the power is lost, which is, again, on the same order of magnitude as reported in [18]. The reason can, again, be found in the plasma impedance, which has with $Z_{pl} = (83 - j125) \Omega$ a notably smaller reactive part, while the resistive part is larger in comparison with the low pressure case. Thereby, more power is dissipated in this branch. Again, this value is generally in line with measurements [16].

It is important to keep in mind that all the results reported here depend heavily on the parameters of choice, i.e., the setup of interest. By choosing circuit elements and a reactor with smaller losses than assumed here, the system circumstantially becomes more efficient. Matching with a Pi-Network leads to different current distributions and, as a result, to different behavior of the whole system.

4. Conclusion

A simulation method for self-consistently simulating CCPs with external lumped element circuits attached is developed based on an equivalent global plasma model. The model is extended to consistently include the calculation of the electron temperature and the plasma density. This is achieved on both a particle balance and a power balance equation of the system. By using the circuit simulation software ngSPICE, a comprising simulation tool is obtained that allows for simulating a system without the need of setting up and solving the differential equations by hand. This tool is readily applicable for a study of the nonlinear circuit/plasma interaction and may also guide the design of external circuits (e.g., a matching network), because parameters like the absorbed power in the plasma, the load impedance and all the intrinsic currents and voltages in the system can easily be obtained.

The versatility of this method is demonstrated by the simulation of a generator, an L-type matching network and loss channels attached to a plasma. It is shown that circular currents in the matching branches arise when the matching conditions are met that lead to power dissipations in the loss elements. These currents are much higher at lower pressures leading to bigger losses compared to simulations performed at higher pressures. For two respective demonstration cases (0.66 Pa versus 200 Pa), the power coupling efficiency is demonstrated to vary substantially (i.e., between about 20% and 90%) for otherwise identical conditions. This emphasizes its intrinsic dependence on the plasma operating regime and the relevance of a simulation-guided approach. Notably, in both cases the nonlinearly created harmonics are found to mostly flow through the stray reactor line and only a small amount reaches the matching network and even less the generator branch.

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