Matching of generators and gas-discharge loads with radio frequency pumping

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Abstract. The article considers the problem of matching power high-frequency generators and gas discharge loads. Variants of various types of tunable matching circuits are proposed. A method of adaptive continuous tuning is described and a variant of implementing tunable elements on varicaps is proposed.

1. Introduction
At present, high-frequency pumped gas-discharge loads are widely used in modern science and technology. An example of such loads is gas lasers, various ion sources, and other devices that use plasma excitation due to high-frequency oscillations. The pumping generators such devices are used transistor or tube generators having a frequency of tens to hundreds of megahertz. In this connection, the high-frequency generator and the plasma discharge may be either inductive and capacitive. Figure 1 shows an example of an ion source with inductive coupling, with a pump frequency of 81 MHz and a pump power of 25 W.

Thus, the impedance of such gas-discharge loads, depending on the design, is both inductive and capacitive, and its actual component can lie in the range from units to hundreds of ohms. With a significant difference in the impedance of the load and the pump generator at high frequencies, the effect of reflection of the useful RF power is observed. The reflection coefficient, of which will be [1]

\[ K_p = \left| \frac{\dot{Z}_{in} - W}{W + \dot{Z}_{in}} \right|^2, \]

where \( W \) is the output resistance of the generator, \( \dot{Z}_{in} \) - is the impedance of the gas discharge load.

There is an urgent problem of matching a powerful high-frequency generator and a gas-discharge load. The problem of matching is complicated by the fact that often the impedance of the gas-discharge load can be estimated only approximately [2].

In addition, the impedance of such loads may change during long-term operation due to the aging effect, depend on the operating mode, gas mixture, etc. reasons. Another feature of the matching is the cases when the working fluid of the load is commensurate with the long wave of the high-frequency pumping energy. In this case, in addition to matching, it is necessary to achieve a uniform distribution of the RF field along with the gas discharge load.
2. Methods
The problem of matching powerful high-frequency generators and loads with varying parameters can be solved using various types of matching circuits [3]. Figure 2. G, T, and P-shaped types of matching circuits with tunable elements are given. Variable capacitors are used as tunable elements, and variable inductance can be obtained by connecting the inductance and variable capacitance in series. Since the impedance of the load has both active and reactive components, the number of elements in the tunable matching circuit should be at least two. By sequentially changing the values of the tunable elements and monitoring the level of power reflected from the load, it is possible to achieve a level of matching when the value of the reflected power is less than 1%.

The use of such matching circuits, however, has several disadvantages. Since the matching process requires the operator, the time of negotiation takes tens of seconds, which is quite critical to the efficiency of the generator at high pumping power since at high values of the reflection coefficient of possible failure of the terminals of the generator stages [4, 5]. Therefore, the matching process is carried out at low values of the generator power, followed by its increase and additional adjustment of the tunable elements in the matching circuit. In addition, the matching procedure requires fixing the reflected power level, which requires the use of a directional coupler and an indication device.

3. Solutions
To significantly increase the speed of matching and eliminate possible human error can apply an adaptive matching circuit [6]. In figure 3 shows a block diagram of an adaptive matching network with a method of continuous tuning [7]. The timing charts for explaining the continuous adjustment method are shown in figure 4.

The power generated by the high-frequency generator (G) enters the load through a bidirectional coupler (BDC) and a feeder, and part of the incident and reflected power through the BDC enters the tuning unit (TB) (see figure 4.a) and figure 4.b)). The tuning block consists of two channels differing in the phase shift of the complex amplitude of the incident wave (0) by 90°. The reflected power signal (see figure 4.c)) is fed to two multipliers X1 and X2, the signal from the generator goes to the other
inputs of the multipliers, directly to X1 and through the phase shifter to (PS) to X1 (see figure 4.d). The signals of the multipliers through a low-pass filter (LPF), filtering high-frequency components, are integrated into integrators that act as memory elements and give the system statism. The output signals of the integrators control the tunable elements X1, …, Xn.

Figure 3. Adaptive matching circuit.  

Figure 4. Timing diagrams.

The continuous tuning method is based on the measurement of the quadrature components of the reflection coefficient \( \hat{K} \). With the known structure of the matching circuit (MC), information on the required direction of tuning of the controlled element can be extracted from the value \( \hat{K} \). Depending on the quadrature components of the reflection coefficient are governed ratings tunable elements X1, …, Xn. If

\[
\hat{U}_r(0) = \hat{K} \hat{U}_{in}(0) = \hat{K} \hat{U}_g,
\]

where \( \hat{U}_g \) - the complex amplitude of the generator signal at the output of the directional coupler.

After the first multiplier, there will be the signal shown in figure 4.e

\[
\hat{U}_{p1} = \text{Re}\left[ \hat{U}_r(0)\hat{U}_{in}^*(0) \right] = \text{Re}\left[ \hat{K} \right] \hat{U}_g^2 \sim n_c.
\]

After the second multiplier, there will be a signal shown in figure 4.f

\[
\hat{U}_{p2} = \text{Re}\left[ \hat{U}_r(0)\hat{U}_{in}(0)e^{j\pi/2} \right] = \text{Im}\left[ \hat{K} \right] \hat{U}_g^2 \sim n_c.
\]

The voltage from the outputs of the integrators is taken either directly or with the opposite sign. It depends on the implementation of tunable elements and on the sign of the phase shift that occurs in the phase shifter by 90°. The stability of a system operating by the continuous tuning method depends on the transmission coefficients of the integrators, namely, on the high-frequency components of the spectrum of the output signal of the integrators that cause a change in the reflected power \( \hat{P}_r \).
Varicaps or reactive lamps can be used as tunable elements [8]. An example of a tunable element on varicaps is shown in figure 5. Varicaps in this circuit is connected in series-parallel. The counter serial connection of the varicaps is necessary to reduce the nonlinear distortions caused by the nonlinear characteristic of the varicap, and the parallel connection increases the nominal value and the range of changes in the capacitance of the tunable element. Chokes \( L_1-L_3 \) are required to prevent the passage of the high-frequency component into the control circuits.

4. Conclusion
Thus, the use of adaptive circuits with tunable matching elements allows using various kinds of discharge loads over a wide range of modes of operation without adjustment and additional adjustment of the matching circuit. In addition, to increase the reliability of the entire system because the magnitude of reflected power does not exceed the critical value which may cause the failure of the RF generator pump. Proposed an adaptive device for matching generators. The device has been tested and has shown the possibility of high-quality matching of the load with the generator when the load changes from 5 to 500 ohms.

References
[1] Fusco V 1990 Microwave circuits. Analysis and computer-aided design Radio and Communications 288
[2] Polushin P A and Samoylov A G 1995 An adaptive pump generator for waveguide lasers Instruments and Experimental Techniques 38(2) 206-11
[3] Zelenov D Yu, Samoylov A G, Samoylov S A 2006 Adaptive matching of high-frequency generators with variable loads Design and technology of electronic means 3 7-13
[4] Titov A A and Ilyushenko V N 2003 Protection of power amplifiers of radio communication systems, FM and TV broadcasting from input overload and output mismatch Radio engineering 12 66-9
[5] Cook R L, Loveless D L and Rudnev V I 2007 Load balancing in modern induction heating systems Power Electronics 2 1-4
[6] Samoylov A G, Samoylov V S and Samoylov S A 2019 The use of adaptive matching circuits to adjust the impedance of high-frequency loads Journal of Physics: Conference Series 1399 IOP Publishing DOI:10.1088/1742-6596/1399/4/044096
[7] Polushin P A, Samoylov A G and Samoylov S A 2000 Adapting high frequency generators for biomedical purposes Medical Equipments 4 26-37
[8] McKinzie W E, Bachmann H and Mendolia G 2013 Adaptive impedance matching module (AIMM) control architectures Patent No.: US 8.620,246 B2