Protection of high frequency generators with unstable load

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Abstract. Methods of adaptive matching of variable load impedance with RF energy sources are investigated. A gradient algorithm for controlling the adaptation process is proposed. Model and full-scale experiments were carried out, which confirmed the effectiveness of the protection of high-frequency generators from fluctuations in load impedance.

High-frequency electromagnetic oscillation generators are widely used in radio communications, control information transmission technology, laser technology, medicine and modern industry. The load of generators usually has the nature of complex resistance (impedance). During operation of high-frequency generators, the impedance changes its value. The reasons for such changes are different. The load impedance changes its value during the operation of high-frequency generators in different modes, during the start-up of the generator, under the influence of aging and due to load accidents, due to the influence of negative factors on the load, such as temperature, vibration, the influence of hydrometeors, etc.

With fluctuations in the magnitude of the load, a mismatch occurs with the output resistance of the generator. In this case, not all energy will be absorbed by the load and part of it will be reflected back to the generator. This leads to a decrease in the efficiency (efficiency) of the generator and failure of its output stages is possible [1-3]. When there is a mismatch with the load of the transmitting devices, the transmission power decreases, additional phase shifts and frequency distortions occur. The reflected signal, returning to the output stages of the transmitter, changes their operating modes, which leads to distortions in the information flow [4,5].

Increasing the efficiency of high-frequency generators can be realized by increasing the energy absorbed by the load, which can be achieved by using automatic adaptive matching circuits (MC), which transform the load impedance into the output impedance of the RF generator. In this case, the following occurs:

- increase in system efficiency;
- the negative effect of reflected energy on the output stages of the generator is reduced;
- there is an opportunity to strictly dose the energy absorbed by the load, which is especially important for medical generators used in physiotherapy.

The principle of operation of the adaptive matching circuit is to analyze information showing the degree of mismatch, and on the basis of this information, rebuild the elements of the adaptive matching circuit to ensure that the generator matches the changed load impedance. As a criterion
characterizing the quality of matching, we can take the level of the signal reflected from the load and, depending on its size, adjust the tunable elements of the adaptive matching circuit, as shown in figure 1.

![Figure 1. Scheme of adjusting the load impedance to the generator resistance.](image)

The generator (G) transmits high-frequency power through a bidirectional coupler (BDC) and a feeder (W) to the MC, which transforms the wave impedance of the feeder W into a changed load impedance. In case of a mismatch, the reflected energy, passing through the central coupler and the feeder, through the bidirectional coupler (BDC) enters the analyzer (A). The working function of the analyzer is to measure the amplitude of the signal reflected from the MC and compare it with the signal of the generator [6]. Based on the analysis of the amplitude-phase relations of these signals, control signals of the digital signal are generated that reduce the magnitude of the reflected power.

In [7], equations were obtained that determine the relationship between the load resistance and the amplitude-phase relations between the signal received from the generator and reflected from the load. These equations determine the algorithm for tuning the adaptive matching circuit

\[
R_l = \text{WRe}\{\dot{Y}\} = W(P_{\text{dir}} - P_{\text{ref}})/(P_{\text{dir}} + P_{\text{ref}} - 2\sqrt{P_{\text{dir}}P_{\text{ref}} \cos \Delta \phi}),
\]

\[
X_l \text{Im}\{\dot{Y}\} = 2W\sqrt{P_{\text{dir}}P_{\text{ref}} \sin \Delta \phi}/\left(P_{\text{dir}} + P_{\text{ref}} - 2\sqrt{P_{\text{dir}}P_{\text{ref}} \cos \Delta \phi}\right).
\]

As a controlled MC, you can use G, P and T - shaped four-terminal on reactive elements. They are easy to calculate and can be built on tunable reactive elements. For low capacities, varicaps can be used, and for high-power devices - reactive lamps. An example of a controlled matching circuit is shown in figure 2.

![Figure 2. Typical L-shaped managed MC.](image)

At least two tunable elements are required to adjust the active and reactive load impedance resistances, and information on the direction of adjustment of the matching circuit elements is required to organize adaptation. To obtain such information can be used various methods. For example, you can determine the values of each element of the MC from the values of n managed elements. You can use a gradient algorithm for determining - of the form:

\[
\frac{\partial X_i}{\partial t} = -a_i f_i, \quad f_i = \frac{\partial U_{\text{out}}[R_{\text{in}}(X_k),X_{\text{in}}(X_k)]}{\partial X_i},
\]
where $X_i$ - is the nominal value of the $i$-th element, $\alpha_i$ - is a coefficient specifying the speed of adjustment, $\{|X_i|\}$ - is the set of denominations of the controlled elements of the MC.

For effective matching, it is necessary to continuously measure the load impedance and, in accordance with the measurement result, rearrange the magnitude of the transformation coefficient of the MC. And to estimate the impedance, it is necessary to find the power $P_{\text{dir}}$ coming from the generator, the power $P_{\text{ref}}$ reflected from the load, and also the phase difference $\Delta \varphi$ between the direct and reflected signals from the load. These parameters can be determined using a bidirectional coupler. The reflection coefficient is defined as

$$CR = \frac{P_{\text{ref}}}{P_{\text{dir}}} = \frac{|Z_l - W|}{|Z_l + W|} = \left(\frac{R_l^2 - W^2 + X_l^2}{(R_l - W)^2 + X_l^2}\right)^2 + \left(\frac{2WX_l}{(R_l - W)^2 + X_l^2}\right)^2,$$

then it’s quite simple to develop an algorithm for determining the load impedance and build an impedance meter.

Such devices were implemented at the Vladimir State University named after Alexander and Nikolai Stoletov and were used in pumping generators of gas CO2 lasers operating in a pulsed mode with sharp impedance surges [3, 7].

Continuous impedance tuning methods have been experimentally investigated. To determine the parameters and study the characteristics of adaptive matching circuits, a model of adaptive DS was developed. The experimental studies were carried out in two stages: both computer models and full-scale installations on the gas-discharge space for studying plasma and on a gas-discharge CO2 laser with RF pumping. Field experiments were carried out with a transmitter loaded onto an antenna with an input impedance of 50 Ohms, with a continuous output power of up to 100 watts. During the experiments, the load resistance (antenna equivalent) varied from 10 to 1000 Ohms. The experiments showed that the adaptive tuning time does not exceed 200 µs, and the generator gives 100% of the output power to the damaged load without changing the operating modes of the output stages.

Three different adaptive adjustment methods for matching were investigated:

- sequential adjustment with sequential adjustment of the branches of the coordination chain;
- parallel adjustment, when all branches of the coordination chain are regulated simultaneously;
- a continuous adjustment method based on a constant analysis of the amplitude-phase relations of the signals reflected from the load and transmitted to it.

The G, T, and P-shaped types of adaptive matching chains were investigated and their characteristics determined. The widest range of possible load impedance has a T-shaped MC. But it has a limitation on the load impedance, in which matching is difficult to achieve [3, 6]. When it is more profitable to use a P-shaped MC. The G-shaped MC has the worst characteristics, since in addition to the analytical constraint, it has an experimentally obtained constraint, in which matching is difficult to achieve with [6, 7].

Figure 3 shows examples of the development of matching processes in the coordinates of the Volpert-Smith diagram with matching in the center of the diagram for $Z_H = W = 50$ Ohm.
In field experiments with a gas-discharge CO2 laser, the matching of an RF pump generator with a power of up to 100 W with a frequency of 125 MHz was studied, and in experiments on a gas-discharge space of a plasma study setup (Fig. 4), the possibilities of the method were studied with a generator with inductively excited plasma with a power of 5 W and frequency 81 MHz. In fig. Figure 4 shows photographs illustrating the efficiency of plasma excitation with an adaptive matching device.

The methods of adaptive matching of variable load impedance with RF energy sources based on the analysis of the amplitude-phase relations of the signal reflected from the load and tuning of the controlled MC are studied. A gradient algorithm for controlling the adaptation process is proposed, which made it possible to synthesize a simple-to-execute and effective adaptive matching device.

The results of model experiments determined the possibilities for the practical use of controlled MCs of various types and the implementation features of adaptive matching devices for industrial RF power generators with variable loads. The results of field tests of an adaptive impedance matching device showed that the loss of high-frequency energy when it is transferred to a changing load is
reduced by more than 10 dB and is less than 1% of the generator power with discrete and smooth load changes in the range from 10 to 1000 Ohms, and the coefficient of useful the action of the RF generator tends to the potential when the generator operates at a coordinated load.

References
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