The use of adaptive matching circuits to adjust the impedance of high-frequency loads

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Abstract. The article discusses methods for matching high-frequency oscillators with variable load. Adaptive impedance tuning methods are described. The results of the experiments are presented. Shown, that losses of high-frequency energy by its transfer to variable loading decrease more than by 10 dB.

1. Introduction

Coordination of the RF generator with the load determines the energy efficiency of the device and its reliability. Overloads of the output stages of generators are the main cause of failures of powerful RF equipment and arise most often due to a mismatch. Coordination is especially important for medical equipment, since it makes it possible to correctly take into account the quantitative contribution of RF power during medical procedures. The task is complicated by the fact that under biomedical unsteady loads, in order to achieve a satisfactory minimum level of reflected RF power, it is necessary to adjust the impedance matching circuit (MC) individually for each specific load.

The consumption of the energy of high-frequency (HF) signal is determined by the matching of the load and the power source (or feeder). The impedance of HF loads may vary while working. This cause can mismatch the source and the load, and valuable indexes of devices will fail. In particular, the change of the impedance of a HF-exited gas-discharge CO₂ laser after alternating the parameters of operation can decrease its emitted optical power greatly. Matching circuits with fixed parameters can’t provide satisfactory matching in wide impedance change. Using adaptive matching circuits is an effective method of improving the matching between the feeder and the load [1], [2], [3].

2. Gradient method

The control of parameters of MC is performed according the level of the signal reflected from the load. The dependence between parameters and the reflected signal is rather smooth function. Gradient methods can be used to control these parameters according

$$\frac{\partial \vec{X}}{\partial t} = -k_i \frac{\partial P_{ref}}{\partial \vec{X}_i},$$

where $P_{ref}$ - reflected power; $\vec{X}_i$ - vector of varying parameters of MC; $k_i$ - some constants of speed of the adaptation process.
To organize the adaptation process, information is needed on the direction of tuning of the tunable elements (PE) of the matching circuit. One of the ways to obtain such information has a search character [1], that is, a small change is made in the current values of the control voltages and the result of this tuning step is analyzed.

Minimum number of components of $X_i$ correspond to number of independent components of $P_{ref}$, in our situation it has two components (due to two orthogonal components of the reflected signal). They depend on active and reactive components of laser impedance. The number of components of $X_i$ can be increased in order to extend the match band of some types of MC.

The main peculiarity is the measuring of the components $\partial P_{ref}/\partial X_i$. It is required to solve the problem of determining a specific tuning element that causes a reaction by changing the value of power reflected from the load. This can be done by various methods. For example, by spacing the adjustment of each channel in time — a sequential adjustment method, or by simultaneously adjusting across all channels using orthogonal control signals — a parallel adjustment method. Consider both of these methods.

3. Sequential adjustment

Such a method can be organized in accordance with the algorithm, the scheme of which is shown in figure 1 [4]. The high-frequency signal from the high-frequency generator (HFG) through the directional coupler (DiCo), feeder (F) and the matching circuit (MC) enters the load (L). The elements of the MC are controlled by voltage from the corresponding adders (S). The number of control inputs must be at least two in order to provide both degrees of freedom when adjusting the impedance.

4. Parallel adjustment

To increase the speed of the adaptive matching circuit, the sequential adjustment of the elements of the MC can be replaced by a parallel adjustment [5]. This will remove one drawback of sequential adjustment. With sequential adjustment, the trajectory of the point in coordinates $\{X_i\}$ can form a closed loop and the matching state far enough from it.

In figure 2 shows an example of the implementation of the parallel adjustment method [1]. The number of adjustment blocks is equal to the number of adjustable elements, which differ in that the low-frequency signal generators (LFG) produce different signals. The transmission coefficients of large-scale amplifiers are regulated by a control scheme (CS).

To perform gradient adjustment, it is necessary that the measurement of $\partial P_{ref}/\partial X_i$ is independent. In a scheme with sequentially adjustment the impedance matching circuit this was achieved by time diversity. In a parallel adjustment measurement independence is ensured by the choice of LFG signals.
Each LFG signal is different from the others. As a set of such signals, you can use any orthogonal basis of functions. The most convenient are sinusoidal signals or meander-type signals for which orthogonality is sufficient so that in the general case their frequencies are different \([6]\). For case \(n=2\) sinusoidal signals of the same frequency can be used, but the phases should be shifted by \(\pi/2\).

The adjustment speed is proportional to the frequency of the signal and the LFG frequency must be equally distributed over the used frequency range.

![Diagram](image)

**Figure 2.** The scheme of parallel adjustment of the MC (AV - averager, LSA - large-scale amplifier, AB - adjustment block, X - multiplier).

The experiments were carried out \([1, 5]\) and the following variants were investigated:

1. Variations of controlling signals of the MC were test signals. Test signals from the orthogonal base

\[
\begin{align*}
S_i S_j &= 0 \\
\bar{S}_j^2 &= \text{const},
\end{align*}
\]

\(S_i, S_j\) – test signals.

Variations of test signals cause variations of matching level and \(P_{\text{omp}}\) and indicate right direction of variations of \(\bar{X}\). Variations of different components were not correlated, it allowed to perform independent measuring.

MC of various configurations were investigated. They contained several controlled reactive elements - varicaps \([7]\). Controlling voltages were formed by summing voltages of integrators and sinusoidal signals of several low-frequency (LF) generators. Frequencies of these signals varied to provide decor relation. The amplitude of the signal (that was reflected from the load) contains the sum of LF components of all LF generators. Controlling signals of all controlled reactive elements were made in correlators and operated corresponding integrators.

The speed of the process of the tuning of MC was determined by amplitude and frequencies of signals of LF generators. The decrease of this speed increased the final accuracy of matching. The increase of the number of controlling reactive elements of MC permits to extend the matching band of circuits and to reduce technical demands to every reactive element.

The speed of the process of tuning may be varied by the manual operation or automatically. The indicator during the auto operation is the final level of mismatching.
2. Variations of the frequency of the HF generator (in permissible bounds) were test signals. Variations of frequency caused variations of reactive resistance and indicated the right direction.

Such variations make differences in active and reactive components of reflected signal. These differences (as functions of frequency) show the direction of controlling reactive elements of MC.

Lacks of this method: correlation between differences and radio frequency depends on the structure of MC; one can need rather wide band of variance of radio frequency in order to provide the demanded accuracy.

3. The joint generation of some HF signals at different frequencies. One of them is a power signal [4], others are test signals. The comparison of reflection at every frequency indicated the right direction of variations of MC. The information about the right direction is contained in correlations of reflected test signals. Lacks of this method: we need to use several generators; the receipt of the information about needed directions of controlling is rather complex; algorithm of controlling is the function of the structure of MC. Last two lacks may be overcome by using analog-digital transformation and microprocessors.

4. Indirect methods. These methods promise to make matching algorithms more simple. We can divide the main equation to some parts. The process of adaptation according every part may be realized separately. Variations of controlled elements are performed according the modified gradient method.

\[
\frac{\partial \bar{X}}{\partial t} = -k \text{Sign} \left( \frac{\partial P_{\text{ref}}}{\partial \bar{X}} \right), \quad \text{Sign} \{y\} = \begin{cases} 
1, & y \geq 0, \\
-1, & y < 0.
\end{cases}
\]

This modification leads to the change of the speed of adaptation. Such fact is not of a great significance.

In order to simplify the realization of MC auxiliary parameters \( \alpha \) are used. By means of these auxiliary parameters the main gradient equations transform in such a way

\[
\frac{\partial P_{\text{ref}}}{\partial x_i} = \frac{\partial P_{\text{ref}}}{\partial \alpha} \frac{\partial \alpha}{\partial x_i}.
\]

Using the modification

\[
\frac{\partial \bar{X}}{\partial t} = -k \text{Sign} \left( \frac{\partial P_{\text{ref}}}{\partial \alpha} \right) \times \text{Sign} \left( \frac{\partial \alpha}{\partial \bar{X}} \right).
\]

It was shown that for some types of MC the first component is constant in wide bounds. These bounds for every type of applied MC were determined.

Parameters \( \alpha \) correspond to phase correlations between the direct and the reflected RF signals. Correlation between \( \alpha \) and parameters of MC were used to variety parameters. Phase correlations between direct signal and reflected signal are measured [5] by means of multipliers. In order to get phase shifted reflected signal some delay devices are used.

The accuracy of algorithms depends on speeds of controlling different reactive elements. One must use standard feeders to improve characteristics of the device. The electrical length of such feeder must be

\[
l = 2\pi \lambda_0,
\]

\( \lambda_0 \) - wavelength of the RF signal in the feeder.

If the length of the feeder is different we must change the phase shift of the reflected signal.
5. Conclusion
Variants of adaptive matching circuits were performed in radio devices. Figure 3 shows high-frequency generators with adaptive impedance matching circuits that were used to pump gas lasers.

![Figure 3. The transistor HF oscillators, protected from overloads, on to output powers: a) 350 W, b) 100 W.](image1)

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