DEVELOPMENT OF REQUIREMENTS TO THE INDIVIDUAL UNITS CHARACTERISTICS OF A HIGH-EFFICIENCY SINGLE-SIDEBAND TRANSMITTER WITH ENVELOPE ELIMINATION AND RESTORATION

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ABSTRACT

Increasing the data transfer rate leads to the use of spectrally efficient types of amplitude-phase modulation, characterized by high values of the peak factor. For energy-efficient amplification of such signals, it is promising to use transmitters built using the Envelope Elimination and Restoration (EER) method. Purpose: further development of methods for using switching operating modes of active elements, taking into account the current state of the element base, increased capabilities of digital signal processing and computer modeling of various transmitter units operation. Development of requirements for the characteristics of EER transmitter units, based on a given level of intermodulation distortions and out-of-band oscillations and development of EER transmitter structural diagram with the possibility of subsequent increase in output power. Methods: an analysis of the requirements for individual units is carried out, taking into account the possibility of their combined influence. Results: a structural diagram of 250 ... 300 W HF range EER transmitter has been developed with the possibility of subsequent increase in the transmitter output power. Variants of implementing output power adjustments have been proposed and requirements for the transmitter exciter characteristics have been developed. Practical relevance: the implementation of the developed recommendations will ensure the fulfillment of requirements for permissible intermodulation distortions of the amplified signal and the permissible level of out-of-band oscillations.

KEYWORDS: *power amplifier; single-sideband modulation; Envelope Elimination and Restoration; energy efficiency; intermodulation distortion; out-of-band emissions.*

1 Introduction

The purpose of this article is to further develop methods for using switching operating modes of active elements, taking into account the current state of the element base, the increased capabilities of digital signal processing and computer modeling of the operation of various transmitter components [1-4]. Ultimately, an approach should be developed to create a highly efficient single-sideband amplifier with a power of 250...300 W in the range of 1.5...30 MHz, as a base cell that can be used in transmitters with an output power of 1 - 5 kW, with technical parameters that meet the requirements for modern radio transmitting devices.

The article analyzes in detail the dependence of the single-sideband transmitter final characteristics, built using the Envelope Elimination and Restoration (EER) method, on the parameters of its components. As a result, requirements for the power amplifier HF and LF paths characteristics have been developed. The requirements for the transmitter exciter and the parameters of its output signal are considered, ensuring, when working together with a power amplifier, the requirements for the quality of the transmitter output signal as a whole are met.

Let us briefly recall the principle of operation of a EER power amplifier constructed using separate amplification of the envelope and phase-modulated component of a single-sideband signal (SSB) [5-8]. The circuit of a power amplifier built using this method is shown in Figure 1.

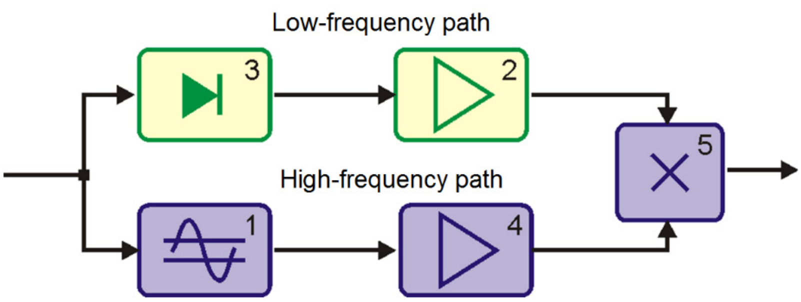

Figure 1. Block diagram of a PA built using the EER amplification method of a single-sideband signal

Here, a signal with single-sideband modulation (SSB) or with any other arbitrary amplitude-phase modulation, such as OFDM, etc., enters two paths - high-frequency and low-frequency. In the HF path of the SSB signal, using amplitude limiter 1, is extremely limited in amplitude. In this case, the high-frequency phase-modulated component of the SSB signal (HF PM) is formed, which is then amplified by PA 4 to the required level. In the low-frequency path, using amplitude detector 3, an envelope signal is formed, which is supplied to amplifier 2. Both signals, amplified in separate paths, are supplied to multiplier 5, for example, to an HF transistor cascade with collector (drain) amplitude modulation. At the multiplier output, the original SSB signal is restored at a given power level.

Since the HF path receives a signal with a constant amplitude, the transistors of this path can operate in switching mode [9]. The low-frequency path must amplify the envelope signal, including the DC component [10]. In this regard, in order to obtain high energy characteristics of the low-frequency path, it must be built using a pulse-width modulation (PWM) scheme, which also allows the use of switching operating modes of transistors. Such a construction of EER paths when performing an ideal multiplication operation in cascade 5 allows, in principle, to obtain high energy and quality characteristics of the transmitter [11]. However, the actual characteristics of the EER PA nodes differ from the ideal ones, which leads to nonlinear distortions of the amplified signal.

This article will consider the main causes of distortions determined by the structure of the EER PA construction, and their impact on the level of intermodulation distortion and out-of-band emissions. In conclusion, recommendations will be formulated on the required output signals of the transmitter exciter, implemented using the EER method of single-sideband signal amplification.

2 Development of EER PA characteristics requirements, based on intermodulation distortion given level

Based on the EER PA operation principle, explained above, and the accumulated experience in creating such devices [10, 11], two types of causes of the amplified signal nonlinear distortions can be distinguished. The first is the reasons that are characteristic of the traditional construction of power amplifiers for single-sideband transmitters. They are associated with the imperfection of the transmission characteristics of the EER PA as a whole (AM-AM, AM-PM), which is mainly due to the nonlinearity and inertia of the characteristics of the element base used. These include:

- amplitude nonlinearity (AM-AM), leading to a change in the shape of the envelope. This nonlinearity can be caused by the dependence of the transmission coefficient of the amplitude detector (block 3 in Fig. 1) on the amplitude of the input signal, the nonlinearity of the envelope amplifier (arising in the paths for generating and amplifying the PWM signal, block 2 in Fig. 1) and the nonlinearity of the multiplier (block 5 in Fig. 1), caused by the imperfection of the amplitude modulation process of the final stage of the RF path;
- parasitic phase modulation (AM-PM) of the RF component caused by the presence of amplitude-phase conversion (APC) in the HF path (in the amplitude limiter and modulated stages of the HF path).

The second group of reasons for distortion of the amplified signal is reasons due to the very principle of operation of the EER PA and the non-ideal characteristics of its individual nodes. These include:

- relative delay of signals in the amplification paths, caused by different inertia of the low-frequency and high-frequency paths and leading to a phase mismatch between the envelope and the high-frequency component;
- frequency distortions of the envelope caused by the nonlinearity of the phase-frequency response and unevenness of the amplitude-frequency response characteristics of the filter circuits of the low-frequency path (in the amplitude detector and power amplifier of the PWM signal);
- instability of the zero level of the low-frequency path (since it is built according to the circuit of a direct current amplifier) under the influence of destabilizing factors, leading to a change in the shape of the envelope;
- the presence of sections with variable amplitude in the HF component, which is caused by incomplete limitation of the input SSB signal.

To assess the influence of the listed factors on the SSB signal distortion, in works [4, 12-14], EER PA and its individual units models were developed, analytical relationships were obtained connecting the levels of intermodulation components at the amplifier output with the parameters of the amplitude, phase-amplitude and frequency characteristics, and the necessary calculations were carried out. Analysis of the results obtained made it possible to formulate requirements for the characteristics of individual nodes, making it possible to ensure the specified linearity of the EER PA as a whole. So, for example, to obtain a level of intermodulation distortion no worse than minus 36 dB, the following conditions must be met:

- instability of the low-frequency path zero level should not exceed 2% of the maximum envelope amplitude;
- the low-pass filter cutoff frequency at the PWM amplifier output (subject to compensation of signal delay in the low-frequency path) must be no less than $3 \cdot f_{oper}$, where f_{oper} is the tone spacing frequency of the two-tone test signal;
- the total parasitic phase deviation in the RF path should not exceed 3...5 degrees;
- the dynamic range of input signal amplitudes limiting in the amplitude limiter block must be at least 26 dB;
- harmonic distortions of the sinusoidal envelope caused by the nonlinearity of the amplitude characteristics of individual nodes, when an AM signal modulated in amplitude by one tone is supplied to the EER PA input, should not exceed 1...1.5%;
- the relative delay of the envelope signal in the EER PA LF path should not exceed 20...30 μs with a test signal tone spacing of 1 kHz.

It is important to note that the above requirements provide intermodulation distortion level of -36 dB when exposed to only one of the considered causes of distortion. In practice, as a rule, several causes of distortion act simultaneously and undesirable intermodulation components can add up algebraically. So, for example, with the simultaneous influence of amplitude nonlinearity and APC with the levels indicated above, each of the reasons will cause intermodulation distortions Kf3 = -36 dB and the level of the resulting distortions will be -30 dB. In light of this, to ensure a given level of intermodulation distortion in practice, one should strive to meet the given requirements 2...3 times more stringent.

As will be shown below, the need to meet these requirements in the development and practical implementation of individual EER PA units largely determines the choice of their circuitry and design solutions and the element base used.

3 Development of requirements for the switching EER PA characteristics, based on the out-of-band oscillations required level

The nonlinearity of the radio transmitter paths determines not only its qualitative characteristics (intermodulation distortion level), but also the parameters of electromagnetic compatibility. One of these parameters is the out-of-band oscillations level. Out-of-band oscillations of a radio transmitter are assessed on a noise-like modulating signal with a uniform spectrum in the frequency band 300...3400 Hz. Such a signal is almost close to the model of modern digital OFDM (Orthogonal Frequency-Division Multiplexing) signal used to transmit data (audio information, texts, images, geographic maps, etc.) over radio channels, as well as used in digital broadcasting, for example, the DRM (Digital Radio Mondiale) standard [15]. Due to the fact that the power amplifier under consideration is a promising development that provides for expanding the bandwidth of signals amplified by EER PA, we will formulate requirements for EER PA nodes when amplifying an OFDM signal of the DRM standard with a bandwidth of 10 kHz. The bandwidth of such a signal allows for three times the data transfer speed compared to the bandwidth of a standard telephone channel.

The work [16] presents the calculations results of the out-of-band radio oscillations levels at the EER PA output on a DRM signal with a 10 kHz bandwidth, caused by amplitude nonlinearity and APC. The results obtained are then compared with the mask of permissible out-of-band emissions for DRM standard broadcast transmitters, which is the most stringent, which will make it possible in the future to use the developed EER PA to create powerful transmitters based on the summation of individual unified modules.

Thus, in accordance with published research results [16], in order to meet the requirements for out-of-band radio oscillations in EER PA, the following conditions must be met:

- instability of the low-frequency path zero level should not exceed 1% of the maximum envelope amplitude;
- parasitic phase deviation in the HF path should not exceed 11.5 degrees;
- the permissible amplitude nonlinearity is determined for two types of nonlinearity, determined by the quadratic and cubic polynomials of the normalized amplitude characteristic:

$$y(x) = ax^2 + x \text{ , and } y(x) = ax^3 + x \text{ ,}$$

where: x and y – normalized envelope at the input and output of the EER PA, respectively. For such types of nonlinearity, the modulus of the parameter "a" should not exceed the value of 0.2 ($|a| < 0.2$), which corresponds to harmonic distortions of the sinusoidal envelope K_{harm} < 10% for a quadratic polynomial and K_{harm} < 4.3% for a cubic polynomial when an AM signal modulated in amplitude by one tone is applied to the EER PA input.

As noted in Section 2, in addition to the imperfection of the AM-AM and AM-PM characteristics, the level of distortion and out-of-band oscillations is significantly influenced by the low-pass filter of the envelope path characteristics - the bandwidth and the permissible delay of the envelope signal. The bandwidth of the optimized low-pass filter of the envelope path [17, 18] with compensated delay should be at least 35 kHz (3.5 times wider than the bandwidth of the amplified OFDM signal), and the permissible relative delay should not be more than 1 μs [19].

Summarizing the research carried out in this section, it should be noted that the most stringent requirements for parasitic APC in the HF path and amplitude nonlinearity are imposed based on the requirements to ensure a level of intermodulation distortion of -36 dB, and the permissible value of the relative delay of HF and LF signals and the bandwidth of the LF path (more than 35 kHz) is determined by the standards for out-of-band emissions.

Based on the requirements for the developed transmitter in terms of intermodulation distortions (-36 dB) and permissible out-of-band oscillations, the maximum phase deviation in the HF path should not exceed 3°...5°, and delay compensation should be carried out with an accuracy of no worse than ±0.2...0.3 μs.

4 Research on ways to organize input signal level adjustments

Typical requirements for the range of the low-frequency path input voltage adjustment are at least -20...+10 dB with a step of 0.25 dB. The analysis of regulatory documentation showed that these requirements relate exclusively to the transmitter exciter, the discussion of which is beyond the scope of this article. This requirement is intended to ensure the nominal level of the HF signal at the exciter output (the nominal power of the transmitter) at different levels of the input LF (speech) signal, determined by the different sensitivity of the microphones used, losses of the LF signal in communication lines, etc.

Providing specified limits for adjusting the input low-frequency signal in modern exciters that widely use digital signal processing methods does not present significant difficulties for specialists when choosing the correct bit depth for digitizing input low-frequency signals.

At the same time, it should be noted that in addition to the requirement to ensure the operation of the transmitter in the rated output power mode, in some cases there are requirements for the possibility of reducing the transmitter power to 25...10% of the nominal value (-6...-10 dB).

The EER PA specificity is that two signals are received from the exciter at its inputs - an HF PM component with a constant amplitude and a LF envelope, which differs significantly from the modulating LF voltage at the exciter telephone channels inputs. In reduced power mode, the exciter must provide a reduced level envelope signal, which, as noted above, is not difficult when using digital signal processing.

The existing experience in the development of switching mode linear power amplifiers built using the EER method (SM EER PA) shows that when the power is reduced by 6 dB (25% of the nominal), the amplifier retains the quality characteristics corresponding to the nominal mode. With a more significant decrease in output power (10% or less), the linearity of the power amplifier deteriorates, due, in particular, to the insufficiency of the dynamic range of the low-frequency path with PWM, associated with the minimum PWM pulse duration realized in practice (≈70...80 ns). To eliminate this drawback, it can be proposed to design the low-frequency path in such a way as to ensure a change in the swing of the triangular voltage in the PWM modulator in proportion to the supply voltage of the final stage (FS) of the PWM modulator (feed-forward principle).

This feature of the low-frequency path, along with other advantages, will allow the EER PA to operate in a low-power mode (10% or less) with a decrease in the FS supply voltage while maintaining the dynamic range of the modulator and, accordingly, the linearity of the entire power amplifier. Reducing the FS PWM supply voltage can be done either smoothly (by accessible adjustment of the output voltage of the +48V power supply) or roughly - by switching the power using a relay to the auxiliary +12V power supply used to power low-power components.

In this case, with the EER PA rated output power, the supply voltage of the final PWM stage is +48V, and the triangular voltage swing at the comparator input in the LF path with PWM is 1.5 V. When switching the PWM FS supply voltage to a +12 V power source (1/4 or minus 12 dB from the nominal value), the triangular voltage swing will also decrease by 4 times and amount to 0.375 V. At the same time, the EER PA output power will decrease by 12 dB, and will be ≈ 6% of the nominal, and the dynamic range of the PWM modulator and its gain will correspond to the nominal mode, which helps maintain the linearity of the power amplifier as a whole and increase its efficiency in low-power mode.

5 Development of an EER PA block diagram with provision of the possibility of subsequent increase in output power

To ensure the possibility of increasing the output power of the transmitter by summing several amplification cells, it is advisable to propose the development of a common signal processing unit (SPU). In this block, the formation and processing of general signals necessary for the EER PA operation can be carried out, which are then distributed to separate unified amplifier modules. Such signals include the HF PM component and envelope of the amplified signal, a triangular voltage to form a PWM sequence, an auxiliary duty cycle limiting pulse, adjustable power supplies of the first stage of the HF path and the bias voltage of the sub-modulator (also known as the drive modulator unit).

This approach will ensure coherence of the PWM clock frequency voltage in individual amplifier cells of a powerful EER PA and the ability to synchronize the clock frequency of the pulsed primary power supply with the PWM modulator clock frequency. This eliminates the possibility of the occurrence of their difference frequencies, which may fall into the passband of the low-frequency path and cannot be filtered without distorting the envelope signal.

In addition, the use of common adjustable voltage sources in the SPU (power supply of the RF path 1st stage and sub-modulator bias) will significantly speed up the procedure for setting up a powerful EER PA containing several unified amplifier modules and simplify the circuit design of each of them, which will increase the manufacturability of the device as a whole.

The proposed EER PA block diagram with 250...300 W output power, shown in Figure 2, contains a signal generation and processing unit (SPU) and a unified amplification cell, consisting of HF and LF paths.

The input connectors X1 and X2 in the signal generation and processing unit are supplied, respectively, with the HF PM component and envelope signals from the exciter designed to work with the EER PA, the requirements for which will be developed in Section 6.

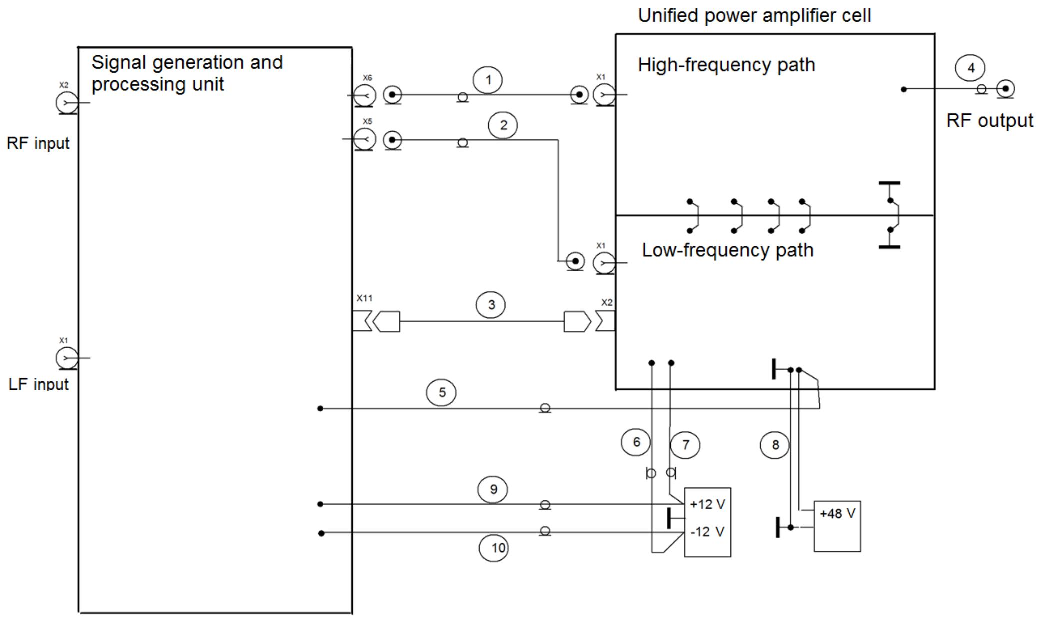

Figure 2. EER PA block diagram with the possibility of subsequent increase in output power

Through connections 1 and 2, made with coaxial cables, signals of the HF PM component and the sum of the envelope with a triangular voltage of the PWM clock frequency are supplied to the HF and LF paths of the unified amplification cell, respectively. Via multi-wire line 3 from the SPU, the PWM duty cycle limiting pulse, the voltage of the regulated power supply of the RF path first stage, and sub=modulator bias voltage are supplied to the amplifier cell. Through connections 6...10, voltages from +48V and +/- 12V power supplies are supplied to the amplifier cell.

To further increase the transmitter output power, 3 more unified amplification cells are added to the EER PA block diagram, which are also provided by input signals generated in the SPU.

6 Development of requirements for the transmitter exciter characteristics built using the EER method

As follows from the EER PA principle of operation (see Fig.1), the exciter of such a transmitter can be built using traditional methods and no special requirements are imposed on it. At the same time, bearing in mind the current widespread use of digital methods for generating various signals, an exciter can be developed specifically designed for use in conjunction with a switching power amplifier. At the output of such an exciter, two signals must be generated - this is the low-frequency envelope of the required single-sideband signal and its phase-modulated component at the operating frequency. The use of such an exciter will make it possible to exclude the amplitude detector and amplitude limiter from the transmitter paths and thereby reduce the nonlinear distortions associated with these nodes.

In addition, the use of digital signal processing methods will provide an adjustable delay of the HF component at the exciter output, which will compensate for the envelope delay that occurs when it is amplified in the powerful LF path of the transmitter. In turn, this will either reduce the level of distortion and out-of-band oscillations at the transmitter output, or simplify the requirements for the characteristics of the low-frequency path.

Thus, in addition to the traditional requirements for the exciter in terms of tuning speed, nonlinear distortions, spurious emissions and noise characteristics, it is necessary to develop requirements for the characteristics of the output paths of the envelope and HF PM component. Based on the analysis of the requirements developed above for the LF and HF paths of the EER PA and the computer modeling carried out, additional requirements for the exciter characteristics were obtained:

- the bandwidth of the envelope output path at the -3 dB level should be ≈ 50 kHz with group delay unevenness in the 0...10 kHz band of no more than 1 μs;
- the bandwidth of the output path of the HF PM component should be ≈ 100 kHz with group delay unevenness in the 60 kHz band of no more than 1 μs;
- the exciter must provide prompt adjustment of the HF PM component delay relative to the envelope within 0...25 μs with a step of no more than 0.2...0.25 μs;
- the level of HF PM component even harmonics should not exceed - 30 dB.

Fulfillment of these requirements with ideal multiplication of the LF and HF components received from the exciter outputs should ensure a level of intermodulation distortion of the generated single-sideband signal no worse than -45...-50 dB with a level of out-of-band oscillations 10...15 dB below the permissible level.

7 Conclusions

As a result of the analysis of methods for constructing highly efficient amplifiers, a block diagram of the HF EER PA with a power of 250...300 W was developed, providing the possibility of subsequent increase in the output power of the transmitter. Options for implementing output power adjustments are proposed and requirements for the characteristics of the transmitter exciter, built using the EER method are developed.

The research carried out made it possible to develop requirements for the characteristics of the EER PA main components, ensuring the necessary quality of the transmitter output signal and meeting the EMC requirements. The main requirements and recommendations for their practical support are as follows:

- the maximum permissible unevenness of the HF path phase-amplitude characteristic is determined by the requirements for the intermodulation distortion level and should not exceed $3^0...5^0$;
- the maximum permissible relative delay of the LF envelope and HF PM component signals is determined by the requirements for the level of out-of-band oscillations and should not exceed 1 μs;

- to make it possible to compensate for the LF envelope delay, the transmitter exciter must provide an adjustable HF PM signal delay in the range of 0...25 μs with an adjustment step of no more than 0.2...0.25 μs.

The implementation of the developed recommendations will ensure compliance with the requirements for permissible intermodulation distortions of the amplified signal and the permissible level of out-of-band oscillations.

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