Compact Non-Linear Power Amplifier for Wideband Underwater and Underground Near-Field Magnetic Communication Systems

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***Abstract*—The paper describes a non-linear power amplifier developed for mobile wideband transceivers of near-field magnetic communication systems. The power amplifier has following parameters: voltage range – up to 200 V; power consumption - up to 200 W; maximum load current – up to 100 A; maximum frequency – 200 kHz; overall dimensions – 100x100x40 mm and weight – ~200 g (without heat sink). Mobile near-field magnetic communication systems equipped with such amplifier are able to provide a voice communication range up to 150 m. The systems can be employed in constructing of various underwater and underground communication networks, for example, in mines or for divers. Results of near-field communication system field testing with the developed non-linear power amplifier are shown. The authors propose a simple algorithm for the main parameters of the power amplifier and the transmitter antenna selection.**

***Index Terms*—Magneto-inductive communications, near-field communications, power amplifier, underground communications, underwater communications**

I. INTRODUCTION

Near-field or magnetic induction communication systems are one of the most promising solutions to transmit data between terrestrial, underground and underwater objects. Near-field magnetic communication systems are intended for non-conventional communication conditions where ordinary communication systems, such as electromagnetic and acoustic ones, cannot be effective [1-3]. Designing near-field communication systems involves several difficulties, but the main problem is communication range extension. The range is limited by the high magnetic signal attenuation that is in inverse proportion to distance cube [1]. Path losses extensively depend on the electrical conductivity of the propagation medium. An operation frequency band of near-field magnetic systems is overloaded by artificial interferences caused by impulse equipment. These interferences pass through power lines from sources for long distances. Consequently, this encourages to use most efficiently energy and spectral resource of communication systems.

The efficiency of communication systems hardware, primarily the transmitter power amplifier, must be increased as well. Power efficient, low weight and small size transceivers, capable to operate effectively on long distances, are required for mobile near-field magnetic communication systems. Compared to other components of near-field magnetic transceivers the power amplifier is the biggest one and consumes the most power. There are some occasions where the transmitter power consumption, weight and size are not critical parameters. For example, when a downstream mine communication system is deployed. However, in mobile communication systems and battery-powered underground/underwater communication networks these are the most important parameters.

II. NEAR-FIELD MAGNETIC COMMUNICATION SYSTEMS BASICS

Conventionally the near-field magnetic communication system consists of a transmitter loaded on a transmitting coil and a receiver that uses a magnetic sensor for magnetic field reception (Fig. 1).

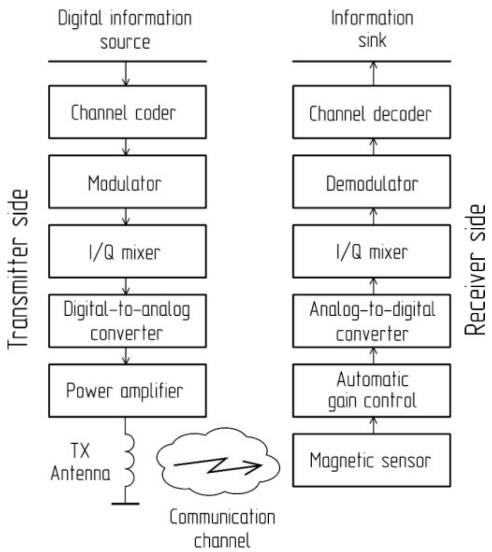

Fig. 1. Near-field magnetic communication system block diagram.

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Modern communication systems are software-defined and the main part of signal processing is implemented on software layer. Data for transmission comes from a digital information source to a channel coder (forward error correction – FEC) and to a modulator. The latter makes a signal complex envelope (baseband signal) that is up-converted to a carrier frequency by a quadrature mixer (I/Q mixer).

The mixer output passband digital signal is converted to an analog waveform by a digital-to-analog converter (DAC) and it comes to a power amplifier. The power amplifier generates current in a transmitter coil antenna. There are two types of power amplifier design. The first type assumes that the amplifier is loaded by a resonance circuit. In the second one, it is loaded by a non-resonance inductance coil. The first type allows a simple high voltage generation on reactive elements of the resonance circuit. However, the high quality resonance system has a narrow frequency band and cannot be used in wideband communication systems. Furthermore, even a low input voltage on the input of the high quality resonance circuit causes high voltages on the reactive elements, up to 1-10 kV, that is not allowable in many cases. Practically, different non-resonance transmitter versions are used in wideband near-field magnetic communication systems.

The magnetic sensor is used for signal reception on the receiver side. It can be a loop or ferrite antenna with a low noise amplifier. However, these antennas receive an electrical component of electromagnetic fields even being thoroughly electrically shielded. The electrical component often carries noise, especially in urban and industrial areas. In order to avoid electrical noise, a thin-magnetic film magnetometer can be used [4, 5]. This magnetometer receives only the magnetic field component, that improves signal to noise ratio (SNR) on the receiver side. A signal from the transmitter coil attenuates rapidly with distance, that requires several stages of an automatic gain control loop (AGC). A dynamic range of the first analog AGC stage must be at least 80 dB in order to provide reliable communication system operating on both short and long distances. An estimation of the dynamic range can be obtained by equations (for free space):

$$B_r = \frac{\mu_0 M \cos(\alpha)}{2\pi r^3} = \frac{\mu_0 NIS \cos(\alpha)}{2\pi r^3} \text{ T}, \tag{1}$$

$$B_\tau = \frac{\mu_0 M \sin(\alpha)}{4\pi r^3} = \frac{\mu_0 NIS \sin(\alpha)}{4\pi r^3} \text{ T}, \tag{2}$$

where B_r – magnetic induction radial component, T;

B_τ – magnetic induction tangential component, T;

$\mu_0 = 4\pi \cdot 10^{-7}$ H/m;

$M = NIS$ – magnetic moment, A·m^2;

I – current in the loop, A;

N – number of turns;

S – loop area, m^2;

α – angle between transmitter and receiver loops, rad;

r – distance, m.

For example, if the transmitter loop has the magnetic moment 30 A·m^2, the transmitter and receiver loops are codirected, the magnetic induction at the distance r_1 = 1 m will be $B_1 \approx 6\cdot10^{-6}$ T, at the distance r_{150} = 150 m will be $B_{150} \approx 1.8\cdot10^{-12}$ T. Hence, the ratio $B_1/B_{150} \approx 3.4\cdot10^6$, that is ~130 dB. For underground and underwater communication systems, signal attenuation will be more significant [2, 3]. Consequently, the dynamic range of the receiver should be as high as possible, especially in cases, when several mobile communication systems work at the same time and in difficult noise environment. Similar requirements are made for the dynamic range of the receiver analog-to-digital converter (ADC).

The power amplifiers in near-field magnetic communication systems work on the inductive load (Fig. 1), that is the difference from block diagrams of modern wide spread electro-magnetic communication systems. In comparison to the classic magnetic loop, whose radiation resistance should be increased for effective generation of electromagnetic waves, the near-field magnetic antenna has a negligible low radiation resistance and cannot be effective for the electromagnetic waves forming. The communication range of the near-field magnetic communication system is defined by the transmitter coil magnetic moment and the receiver sensitivity. The magnetic moment is directly proportional to the coil area, number of turns and the coil current. Hence, it is necessary to increase the current of the multiturn coil in the case of antenna size limitation. That requires a special power amplifier to be developed.

III. The Power Amplifier Design

The power amplifier for mobile near-field communication systems and networks must be of a limited size. In mobile underwater/underground communication systems, for example, the loop size must be less than 0.25 m^2 in order to be placed with a person. Whereas the magnetic moment for providing, for example, 150 m voice communication distance must be more than ~30 A·m^2, that demands about 120 ampere-turns at this loop area. For the transmitter coil with 4 turns, for instance, a current value of the coil must be more than 30 A. High load current is a reason to devote a special attention to the power amplifier performance, particularly when communication nodes have a battery supply. Fig. 2 shows the power amplifier block diagram.

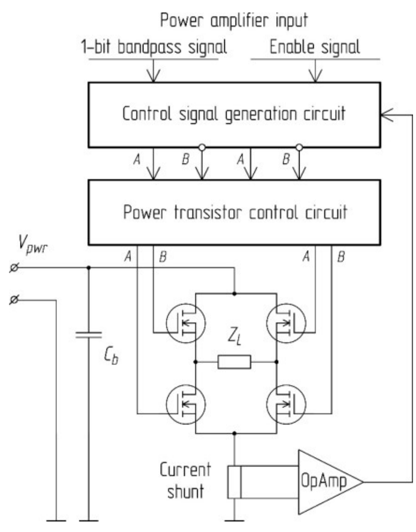
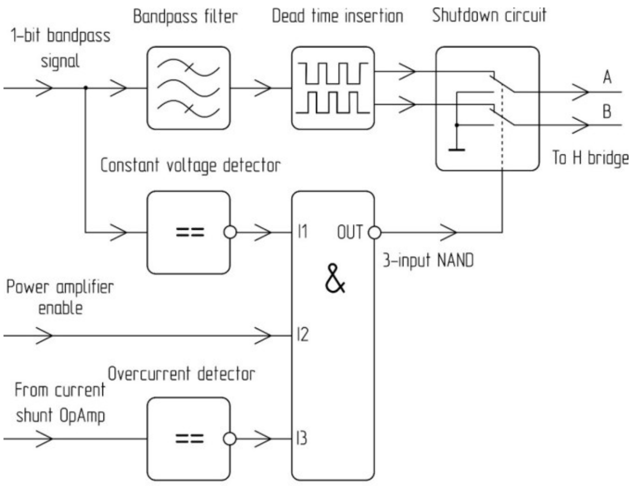


Fig. 2. The power amplifier block diagram.

Power transistors of the amplifier must work in a pulse mode in order to improve the power amplifier efficiency (class-D amplifier). The power amplifier can operate in the non-linear mode when frequency (FSK) or phase (PSK) modulations are used for data transmitting, since a signal amplitude does not carry information in these cases. Although, the non-linear power amplifier mode creates side lobes in a spectrum of the transmitted signal, that can be the interfering signals for other communication systems. In the non-linear mode the amplifier can be realized as a simple H bridge voltage invertor controlled by a one-bit signal from the modulator.

The digital signals on the carrier frequency from the modulator arrive to a control signal generation circuit. The circuit has four output signals for controlling power transistor drivers. A dead time circuit is used in order to avoid through current; the input signal passes through a bandpass filter. Low frequencies are blocked in order to avoid high current through the inductive load. High frequencies are limited in order to prevent changing of the power amplifier operational mode to linear, when pulses duration is comparable to the transition time of the power transistors. Fig. 3 shows the control signal generation circuit.



PA enable	Constant voltage	Overcurrent	PA status
HIGH	NO	NO	WORK
LOW			SHUTDOWN
HIGH	YES		
LOW			
HIGH	NO	YES	
LOW			
HIGH	YES		
LOW			

Fig. 3. Control signal generation circuit.

Every bridge power transistor is controlled by a high-speed driver, which consists of: an isolated switching power supply with a bipolar output relatively to a transistor source; a high-speed isolation circuit of the input signal; a powerful ultrafast MOSFET driver IXDD630, that can source/sink up to 30 A of gate peak current; snubber circuits and other protection circuits. Fig. 4 shows a part of the power transistor control circuit for one power transistor.

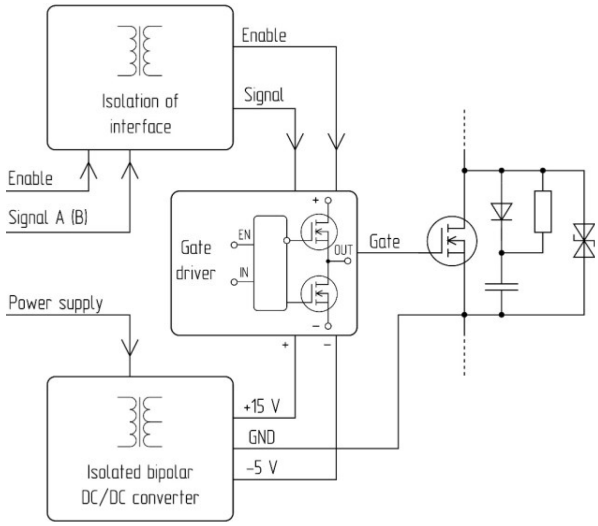


Fig. 4. The part of the power transistor control circuit (for one power transistor).

Fig. 5 shows the proposed power amplifier construction (power supply and signal connections are not shown).

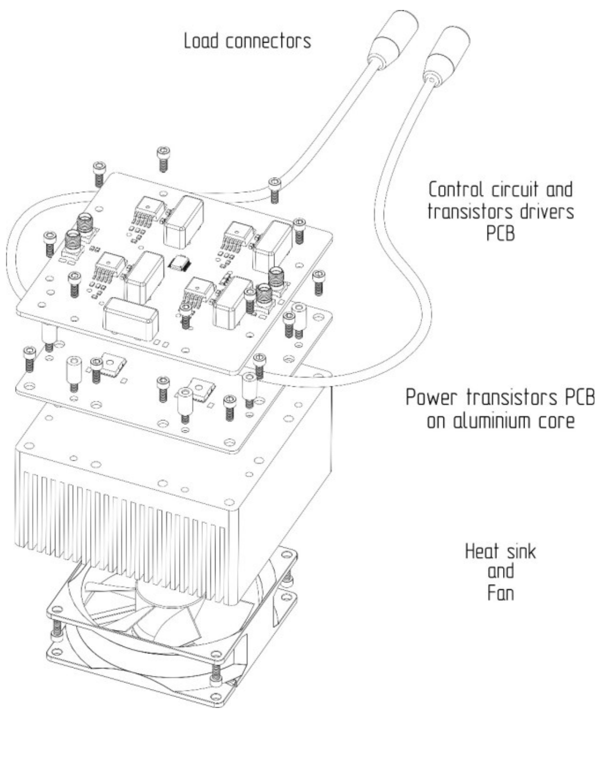


Fig. 5. The power amplifier construction.

The power transistors in HSOF-8 package are placed on an aluminium-based PCB that allows good heat transfer to a heat sink. Depending on the value of the power supply voltage and the carrier frequency various transistors can be mounted on the PCB, for example, IPT012N08N5, IPT059N15N3, IPT210N25NFD and others. Total power dissipation on the transistors can be up to 200 W. That demands an active cooling system, including the heat sink with a fan.

The voltage invertor blocking capacitors, the snubbers and the protection circuits are placed near the power transistors on the aluminum-based PCB. The transistor drivers are located on a multilayer PCB directly above the transistors. That allows shortening conductors length between the boards as much as possible. The power supply and control supply voltages are isolated and can be provided by different sources.

Since the power amplifier works on the reactive load with the inductive reactance, the reactive energy is exchanged between the transmitter coil and the capacitor bank (C_b on Fig. 2). Hence, a capacitors loss tangent must be better than $\sim 10^{-3}$ on the carrier frequency in order to avoid high power dissipation. In case of high current operation, external blocking capacitors are needed to be used. The blocking capacitors parameters are chosen according to the carrier frequency of communication systems. When the communication system carrier frequency is lower than 100 kHz, for example, the capacitor B32678G3606K000 can be used. Its capacitance is 60 uF, rated voltage is 300 V and its series self-resonance frequency (where losses in capacitor are maximal) is higher than the carrier frequency. The photograph of the power amplifier prototype is shown on Fig. 6.

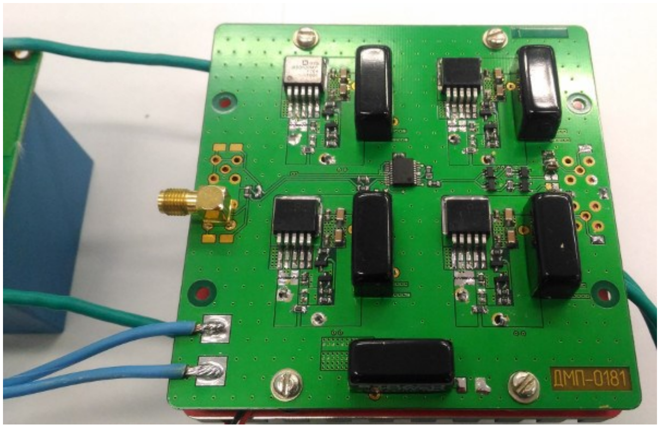


Fig. 6. The power amplifier prototype.

The power amplifier was successfully tested in laboratory environment under the following conditions: power supply voltages – up to 200 V (power transistors IPT210N25NFD are used for high voltage testing); load current – up to 100 A (power transistors IPT012N08N5 are used for high current testing); carrier frequencies – up to 200 kHz.

IV. Tests of the Near-Field Communication System

The power amplifier was installed to a portable near-field magnetic communication system. The communication system is intended for voice transmitting and uses the developed power amplifier for current generation in the transmitter coil.

Table I shows near-field mobile magnetic communication system parameters. Field tests of the magnetic communication system were carried out in an open space, away from any magnetic noise sources in order to verify a link budget for free space.

TABLE I
NEAR-FIELD COMMUNICATION SYSTEM PARAMETERS

Parameter		***Value***	***Unit***
Transmitter			
Carrier frequency		20	kHz
Modulation type		BPSK	
Transmitter antenna (loop antenna)	area	0.2	m^2
	number of turns	4	
Power supply voltage		100	V
Load current		40	A
Transmitter loop magnetic moment		30	$A \cdot m^2$
Amplifier power consumption, max		140	W
Receiver			
Receiver amplitude noise spectral density (in working frequency band)		10^{-14}	$T/Hz^{1/2}$
Receiver frequency bandwidth		5	kHz
Signal-to-noise ratio at distance 150 m (for radial component)		8	dB

Before testing of voice transmission, the link budget was measured by transmitting a continuous sine wave. The magnetic field, which was created by the transmitter antenna, at the receiver side was measured by the thin magnetic film magnetometer [4, 5] and a spectrum analyzer. It is very important to measure an interference spectrum at the testing area before tests starting, because even in the open space own measurement equipment (spectrum analyzers, power sources and power converters, laptops and so on) can be a source of interferences in the working frequency band.

Voice data for transmission were formed from an analog microphone by analog-to-digital conversion and data compression (vocoder). A digital data rate was 2.4 kbps. The carrier frequency of the transmitter could be chosen from 5 kHz to 200 kHz, but it was fixed at 20 kHz during the test in order to get an optimal working mode of the power amplifier with the required magnetic moment of the transmitter antenna. The rectangular transmitter coil had 4 turns of the litz wire 1000x0.1 mm, the area of the coil was 0.2 m^2. The total length of the antenna litz wire was about 8 m. 100 V for power amplifier was created by a portable DC/DC converter from 6 cell lithium-ion polymer battery. The communication system modulation type was a binary phase-shift keying (BPSK). An equal loss resistance in the power amplifier and the coil antenna was less than 0.1 ohm, that determined a power amplifier consumption – less than 140 W. This heat power was distributed between the power amplifier and the coil antenna. As a result, the transmitter antenna had the required magnetic moment $\sim 30\ A \cdot m^2$.

All measurements were carried out at pickets which were placed every 10 m from the transmitter antenna up to the 150 m point. Fig. 7 shows results of the communication system test during sine wave transmission. There is a good similarity of the practical results and calculations performed by equations (1, 2) for free lossless space. The results can be used, for example, for designing near-field magnetic communication systems for divers, which work in fresh water with low conductivity.

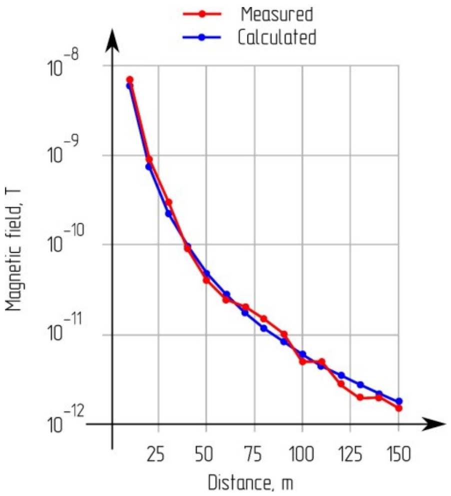


Fig. 7. The results of the communication system test.

The calculated signal strength at distance 150 m is about $1.8\cdot10^{-12}$ T; measured by thin magnetic film magnetometer value is ~$1,6\cdot10^{-12}$ T (Fig. 7). Noise value at the receiver input for 5 kHz signal bandwidth and for noise amplitude spectral density 10^{-14} T/Hz$^{1/2}$ is ~$7.1\cdot10^{-13}$ T. That gives a signal-to-noise ratio ~8 dB (Table I). It is sufficient for voice communication with the selected signal-code sequence. The voice transmission test successfully confirmed these calculations: a boundary of stable communications was at the distance of 140–150 m.

V. Results and Discussion

Near-field magnetic communication systems allow to create communication links in difficult environments, but even for free space the signal power is inversely proportional to six power of the distance between the transmitter coil and the receiver magnetometer [1-3]. That demands creating transmitters with as high magnetic moment as possible. At the same time overall dimensions, the size and the power consumption are critical parameters for mobile communication systems.

Moreover, the communication systems work not only in budget deficit conditions, they work in a poor interference environment, especially in urban and industrial areas. Thus, it is necessary to use special signal-code sequences and modulation schemes. For example, an orthogonal multicarrier modulation with coding (adapted COFDM) can be utilized. Since the non-linear power amplifier is more effective for mobile applications, COFDM must be adapted to work with one-bit DAC.

The transmitter loop magnetic antennas with the high magnetic moment are required in order to provide long distance near-field magnetic communications. It is difficult to realize the high magnetic moment with limitations of loop area. One possible way to increase the magnetic moment of the mobile near-field transmitter is to use modern silicon carbide transistors working at high voltages and having low losses. The high voltage amplifier is loaded by the multiturn coil with a low current, thus a low power dissipation is provided. The transmitter antenna must be made of an optimal litz wire.

In several cases a toroidal core transformer can be used for the current conversion in the transmitter antenna [6], but it increases overall dimensions and the size of the power amplifier, especially for high power transmitters.

The authors propose a next simple algorithm of the power amplifier and antenna main parameters choosing:

– Select maximum as possible the power amplifier supply voltage. The supply voltage should be safety for users, appropriate for the power transistors (it is necessary to work in safe operating area (SOA) of selected transistors), possible for creating by DC/DC converters from standard voltages and so on.

– Select the appropriate antenna size and the big random number of the antenna turns, for example 100 or more. Estimate next antenna parameters: the antenna inductance, reactance and ohmic resistance at working frequency; the antenna current for the selected supply voltage at the working frequency; the antenna resistance loss; the antenna magnetic moment. The total resistance loss can be estimated by summarizing the antenna loss and the power amplifier loss (drain-to-source resistance and transition losses in the power transistors, power capacitors losses, losses in connectors and wires, etc.).

– Repeat last item decreasing the antenna turns until you get the required magnetic moment and (or) the maximal power consumption.

– Change initial conditions and repeat calculations if it is necessary.

The receiver antenna should be a 3-axial magnetometer. It is important to use shielded coil magnetometers or another types which do not receive the electrical component of electromagnetic waves because of the difficult noise environment. The authors use a 3-axis thin-magnetic film magnetometer [4, 5], which is not sensitive to electrical fields, has a wide frequency bandwidth, high sensitivity, low overall dimensions and low weight. The receiver must have 3 input channels for parallel processing signals from a 3-axis magnetometer in order to provide stable communications at any angles between the transmitter antenna and the receiver antenna.

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