Approach to Implementation Full-duplex Communication Technology in Power Line Communication Systems

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***Abstract* – Power line communication systems, which are widely used for smart home systems, the industrial Internet of things, can be used in aviation and space technology. One of the important problems of power line communication systems is the need to increase spectral efficiency, since operation is possible in the frequency range up to 30 MHz, limited by high attenuation of signals at higher frequencies. The use of technology of full-duplex data transmission via power circuits will allow up to 2 times increase spectral efficiency. This article describes approaches to the implementation of this technology, outlines the main problems to be faced and ways to solve them. We have proposed the most effective approach in our opinion to compensate for the signal of our own transmitter in the receiving channel.**

***Index Terms* – full-duplex communication, analog cancellation, power lines, data transmission system, circulator.**

I. INTRODUCTION

TELECOMMUNICATION TECHNOLOGY is called Power Line Communication (PLS) if it uses power supply networks to transmit data as a physical environment for signal transmission instead of radio or specially organized cable lines. [1].

The use of PLC technologies allows one to reduce the cost of introducing new telecommunication networks. Therefore, high and low voltage networks can be used for internal communications in industrial and residential buildings, household appliances, spacecraft, vehicles, for solving problems of remote measurement and control of operating parameters of various devices connected to the power supply network.

The difficulty of organizing communication using electrical networks is the need for high-voltage isolation of equipment for transmitting and receiving signals, operation at high level of interference, significant signal attenuation and fluctuation of the main channel characteristics over time.

The PLC channel contains both pulsed (broadband) and narrowband interference [2]. Narrowband interference in the channel occurs due to the operation of various electrical devices connected to power supply network, for example, secondary power sources create powerful interference (-20 dBW) in the frequency range from 30 kHz to 200 kHz. Broadband interference is caused by transients during the operation of electrical devices, as well as when they are switched in power networks.

PLC systems can be divided into two groups: systems operating in a narrow frequency band that provide communication with a relatively low data transfer rate of up to 100 Kbps, and broadband PLC systems covering a frequency range from 1 MHz to 30 MHz and reaching data rates up to 500 Mbps under certain conditions.

For data transmission systems via power circuits, as well as for any other communication system, the task of more efficient use of the time-frequency resource is relevant. One solution to this problem is to use full-duplex data technology, when the transmission and receiving of signals are carried out simultaneously in the same frequency band. Thus, there is no time or frequency separation of the transmitted and received information. This allows increasing the efficiency of using the time-frequency resource up to 2 times. This technology can be successfully applied not only in wireless systems, but also in data transmission systems via power circuits.

The implementation of full-duplex communication technology in data transmission systems via power supply circuits is probably a simpler task than its implementation in wireless communication systems. Since the main idea of full-duplex communication is cancellation in the receiver (RX) of a powerful transmitter signal, it is much simpler to implement this at low frequencies than at frequencies used by wireless communication systems. Analog, digital, and analog-to-digital cancellation methods are used to suppress the transmitter signal in the receive path. The main problem when using existing methods of cancellation in the receiving path of the transmitter signal, when working in the power supply circuit, is the inconstancy of its characteristics and significant distortions of both the useful signal and the compensated signal of the transmitter (TX) as a result. At the same time, the obtained cancellation level (-20 ...- 30) dB is insufficient for the full-fledged functioning of the full-duplex data transmission mode [3].

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II. Overall Concept Of Creating A Full-Duplex Power Line Communication System

The full-duplex power line data transfer system is very similar to analogous solutions for wireless communication. The problem of full-duplex data transmission systems without time and frequency separation is that the powerful signal of its own transmitter at the output of the amplifier enters the receiving channel and interferes with the reception and processing of the useful signal from the remote transmitter. Further in the article, the term “useful signal” is used to indicate a useful signal from a remote transmitter, and the term “interference signal” is used to denote a signal of its own transmitter entering the receiving channel.

The power of the interference signal in the receiving channel can be 100 or more dB higher than the power of the useful signal from the remote transmitter. For the operation of a full-duplex communication system, it is necessary to provide isolation of more than 80 dB between the transmitting and receiving channels. In the receiving channel for full-duplex communication system interference signal cancellation is performed both in analog and digital form for these purposes.

The main idea of analog cancellation methods is that the formation of the cancellation signal occurs in the radio frequency range, before the analog-to-digital converter. The cancellation signal must be identical to the interference signal of its own transmitter, but in counterphase [4].

Digital cancellation is used to additional suppress the interference signal, which can significantly increase the overall level of cancellation in a full-duplex communication system.

Fig.1 shows a structural diagram of the general concept of creating a full-duplex power-line communication system, which includes a matching circuit with an electric network, an analog and digital cancellation circuit.

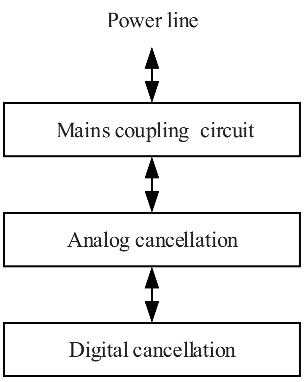

Fig. 1. Overall concept of creating a full-duplex power line communication system.

The matching scheme with the power supply network is a circuit that provides high-voltage galvanic isolation of the transmission and receiving paths from the network, as well as matching with the approximate impedance of the power supply network.

III. Analog-Digital Cancellation For A Full-Duplex Power Line Communication System

A. The main disadvantages of the known analogue cancellation schemes

There are many different interference suppression schemes for full duplex communications [5, 6]. The main differences of the known cancellation schemes are in the method of generating a compensating signal. For example, an analog suppression circuit uses a tunable phase shifter and attenuator in Fig.2. A compensating signal is generated by phase shifting the main signal of the transmitter and then attenuated. The main disadvantage of this circuit is that the transmitter signal usually has a high power level (0 ... 7) dBW and goes to the adder of the cancellation circuit with almost no attenuation. This means that the compensating signal has strict requirements regarding its conformity to the interfering signal. The signal goes to the sensitive input of the receiver with unacceptable power for it even in the case of the slightest difference between the interference signal and the cancellation signal. In turn, the adder in the cancellation circuit should work at high power levels of the input signals. Another disadvantage of this scheme is that when operating in a branched electric network, the interference signal is a strongly distorted signal of the local transmitter due to the multipath propagation of the signal caused by the difference and inconsistency in time of the wave impedance of the network, especially in a wide frequency band. But the compensation signal is generated from the undistorted signal of the transmitter and is not subject to distortion. This makes it impossible to compensate for the interference signal.

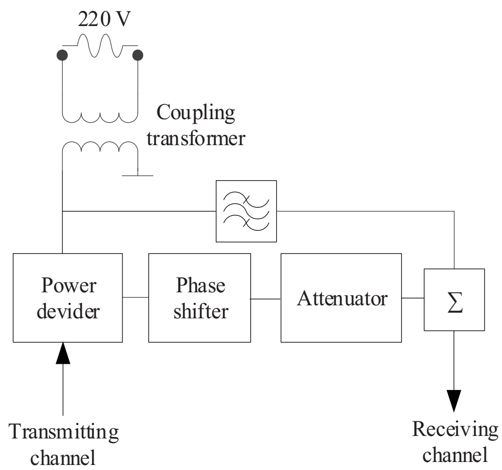

Fig. 2. Cancellation analog circuit using tunable phase shifter and attenuator.

Another well-known method of analog cancellation is the method using a balancing transformer, it is shown in Fig.3.

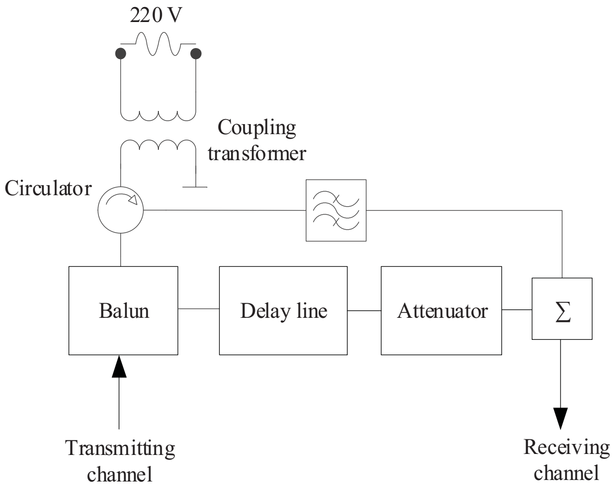

Fig. 3. Cancellation analog circuit using a balancing transformer.

In the diagram in Fig.3, a cancellation signal is generated from the transmitter signal using a balancing transformer, which acts as a phase shifter and rotates the signal phase strictly 180 degrees. The delay line and attenuator are used to match the interference signal and the cancellation signal for delay and amplitude. The main difference from the circuit shown in Fig.2 is the attenuation of a powerful transmitter signal in front of the cancellation circuit using a circulator. In this scheme, as in the previous one, the suppression of the interfering signal is not efficient enough, due to the difference between the interference signal and its compensating signal because of the influence of the electric network on the shape of the interference signal.

It is also worth noting that implementing a delay line for an analog signal, especially with tunable delay, is a very difficult task.

Another disadvantage is not the ideal frequency response of the balancing transformer. Therefore, counterphase signals are not provided in the entire output frequency band.

Fig.4 shows the cancellation scheme using a two-channel digital-to-analog converter.

The main difference between this scheme and the ones considered above is the formation of a cancellation signal using an additional digital-to-analog converter. This is an advantage of this implementation, since the phase-shift of the compensating cancelation signal is performed digitally and does not depend on the frequency in the working frequency band of the communication system.

The disadvantages include a large signal level at the input of the summing circuit, the use of two power amplifiers for each digital-to-analog converter, and high requirements for their identity, as a consequence.

All analog cancellation schemes discussed in this chapter for the implementation of a full-duplex communication system have some drawbacks that do not allow providing a sufficient level of interference signal cancellation (-80 dB) for full-duplex communication system.

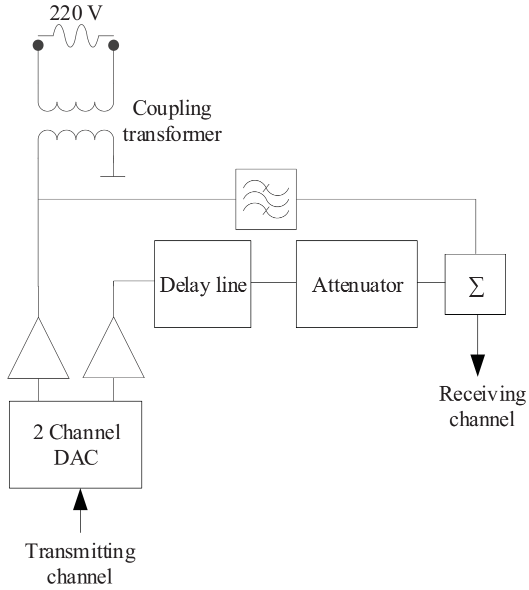

Fig. 4. Cancellation analog circuit using a two-channel digital-to-analog converter.

B. Approach to the implementation of analog-to-digital compensator.

Based on the analog interference signal cancellation schemes discussed in the previous chapter in a full-duplex communication system, an approach was proposed to implement the analog-to-digital cancellation scheme, which is presented in Fig.5.

The analog part of the cancellation scheme shown in Fig.5 includes the blocks described below.

The mains coupling and protector circuit is a circuit that provides galvanic isolation of the transmitting and receiving devices with the network, as well as matching with the approximate impedance of the electric network. The protection circuit guarantees the safe operation of the following highly sensitive receiver nodes under the influence of various types of impulse noise emanating from the network.

The high-pass filter (HPF) does not allow overloading of subsequent sensitive nodes of the receiver due to the influence of the network frequency signal (50 Hz) and strong interference from household appliances located in the low-frequency range from 50 Hz to 200 kHz. The filter should have a frequency response slope of at least 160 dB per decade. This corresponds to an eighth-order Butterworth filter and a cutoff frequency equal to the lowest operating frequency.

The electronic circulator (Electronics circulator) is designed to attenuate the signal of the local transmitter on the receiving side due to the one-way signal transmission from the transmitting port of the circulator to its output port connected to the electric network. The circulator will also transmit the input useful signal from the port connected to the network to the port of the receiving part. The decoupling level of the transmitting path by the circulator from the receiving path should be at least 40 dB. The electronic circulator for the frequency band from 1 MHz to 30 MHz can be performed according to the Wien bridge circuit and operational amplifiers playing at the same time the role of a preliminary amplifier of the receiving path.

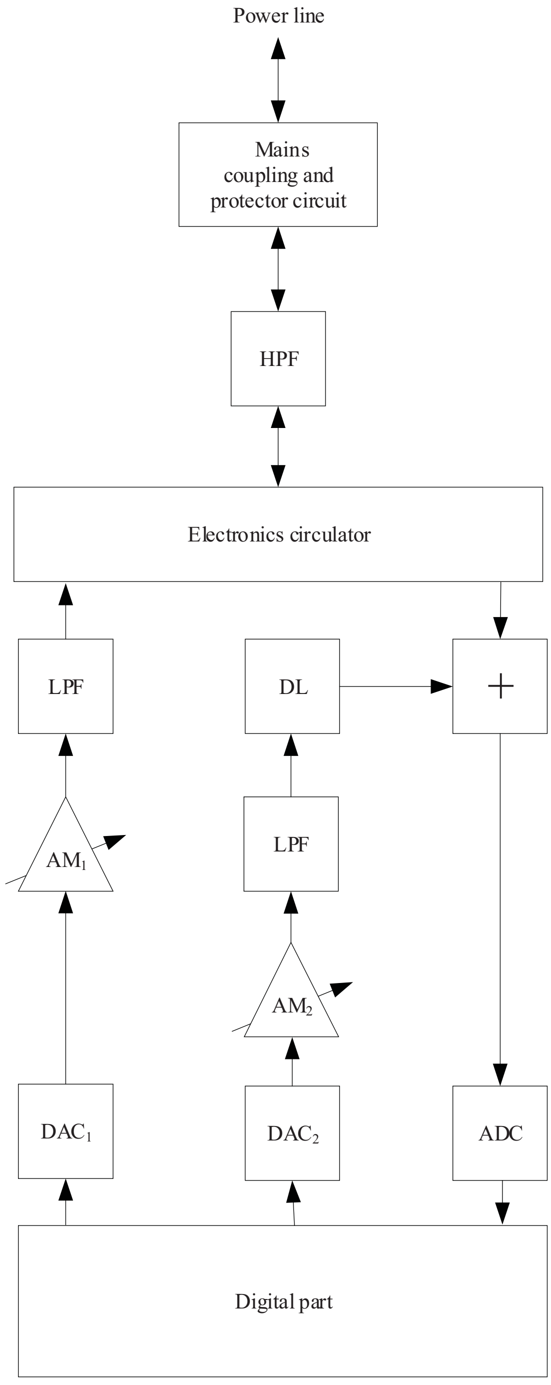

Fig. 5. Analog-to-digital cancellation circuit.

Digital-to-analog converter (DAC) converts a digital signal into an analog signal. An analog-to-digital converter (ADC) performs the reverse function.

The low-pass filter (LPF) is designed to suppress the mirror channel in the signal spectrum after digital-to-analog conversion, as well as products of intermodulation of the power amplifier. This filter should have a frequency drop of at least 120 dB per decade, which is a sixth-order Butterworth filter, and a cutoff frequency corresponding to the highest operating frequency.

A broadband power amplifier (AM) is needed to amplify the DAC signals of a transmitter in terms of power to provide a specific communication range. A typical signal level from the DAC output in a frequency band of 30 MHz wide is -45 dBW, while the power level should usually be from 15 dB to 40 dB when the signal power at the amplifier output is from 0.01 W to 3 W, depending on the required communication range.

The delay line (DL) is necessary for the temporary matching of the signal-interference with the compensating signal.

In view of the difficulties with the implementation of the delay line in the analogue part in modern Field-Programmable Gate Array (FPGA) models, it is possible to implement it in the digital part.

The adder performs the addition of the signal arriving at its input from the communication channel with a compensating signal. It can be implemented on an operational amplifier for the greatest isolation between the channels of the terms.

The following are simulation results of an electronic circulator variant using the Wheatstone Bridge.

Fig. 6 shows a diagram of the electrical principle of an electronic circulator. The model includes a TX transmitter with output impedance Z1, an RX receiver with input impedance Z3, a PLC channel CH with input impedance Z2. The circulator is formed by the Watson bridge on the elements R1, R2, R3 and the channel resistance Z2 and the operational amplifier U1 [9, 10]. In the simulation, the TX transmitter signal cancellation level at the RX receiver input and the transmission gain were measured. The simulation was carried out at the minimum (Z2 = 50 Ohms) and maximum (Z2 = 150 Ohms) value of the input impedance of the network Z2, as well as with the value of the input resistance equal to the geometric mean between the minimum and maximum values (Z2 = 86.6 Ohms). The values of the resistances R1, R2, and R3 did not change during the simulation. They were equal to the geometric mean value between the minimum and maximum values of the channel input resistance, R1 = R2 = R3 = 86.6 Ohms. The accuracy of setting the bridge resistances was 0.1 Ohms. Also during the simulation, the transmission gain of the TX transmitter signal to the CH channel was estimated. This was done to estimate the direct transmission loss of the transmitter signal to the PLC channel.

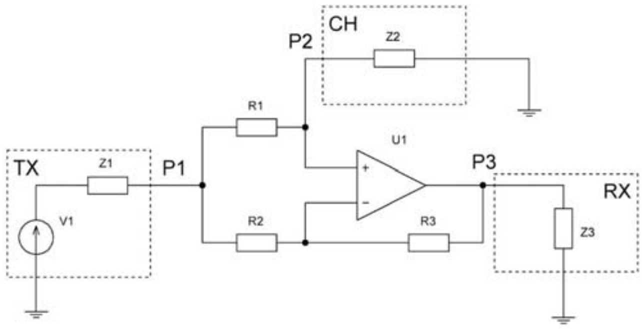

Fig. 6. Electric schematic diagram of the electronic circulator model.

Table I presents the simulation results of the electronic circulator circuit.

TABLE I
SIMULATION RESULTS OF ELECTRONIC CIRCULATOR

Channel Impedance, Z2 Ohm	Power at the transmitter P1, mW	Power at the receiver P3, mW	Transmitter signal power in power lines P2, mW	Transmitter signal cancellation level at the receiver input, dB	Transmitter signal transmission gain in power lines, dB
50	11.14	1.1	2.04	-10.05	-7,37
86.6	9.28	5.36	2.32	-62.4	-6
150	7.18	1.22	2.27	-7.69	-5

From the data presented in Table I, the simulation data of the electronic circulator shows that this circuit is sensitive to changes in the input resistance of the PLC channel at constant values of the resistances R1, R2, and R3. The cancellation level of the transmitter signal at the receiving part varies from -7 dB to -62 dB. Evaluation of the transmission gain of the transmitter signal to the channel indicates power losses of up to -7 dB and even -6 dB when the circulator is matched with the channel R1 = R2 = R3 = Z2. The simulation results of the proposed version of the electronic circulator indicate the need for accurate tuning of the circuit elements to obtain a satisfactory level of interference signal cancellation.

As previously mentioned, the interference signal arriving at the input of the receiving part is the signal of the local transmitter distorted by the influence of the power supply network. In this regard, it is necessary to take these distortions into account when forming a compensating signal. For these purposes, a predistortion block is provided in the digital part of the cancellation scheme. The block diagram generating a signal for analog cancellation in the digital part is shown in Fig.7.

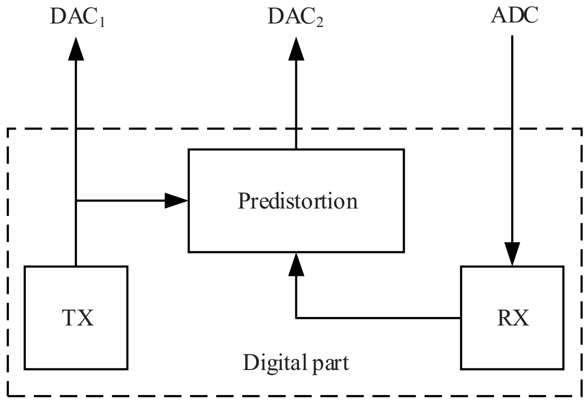

Fig. 7. Digital part of analog-to-digital cancellation circuitry.

It is possible to use digital cancellation to further suppress the interference signal along with a digital-to-analog cancellation circuit. The scheme is largely similar to the analog cancellation scheme, but is implemented in the form of algorithms in a digital circuit. Fig.8 shows a block diagram of digital cancellation.

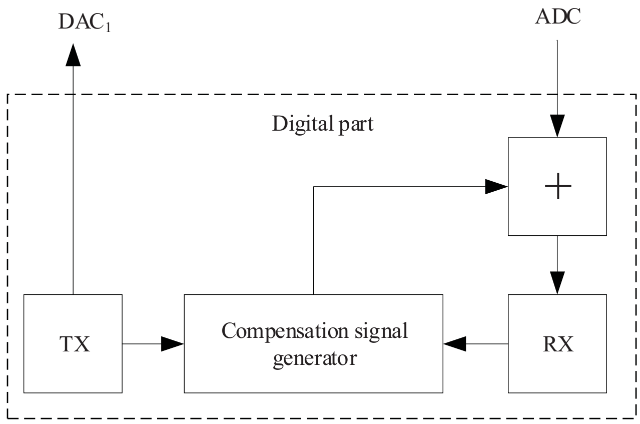

Fig. 8. Digital cancellation block diagram.

IV. CONCLUSION

Thus, the article considered the possibility of implementing a full-duplex communication system for power circuits, described various options for well-known analog cancellation schemes, and their disadvantages were identified. A structural diagram of a digital-to-analog compensator, devoid of many of the disadvantages of previously known circuits considered, is presented and examined in detail. A structural diagram of a digital-to-analog cancellation, devoid of many of the disadvantages of previously known circuits considered, is presented and examined in detail. A simulation of the electronic circulator version using the Wheatstone bridge to cancel interference signal is carried out. From the simulation results it is clear that for this version of the electronic circulator, it is necessary to fine tune the input impedance of the PLC channel. Given the dependence of the impedance of the power lines on time and the connected load, it is necessary to make continuous adjustment. The achievable compensation level is at least -60 dB. The accuracy of the bridge resistance settings is not more than 0.1 Ohms. The disadvantage is the loss of signal power of the transmitter on the resistive elements of the bridge. This negatively affects the operation of the circulator with a high transmitter signal power. In general, we can conclude that it is necessary to use analog and digital methods of interference signal cancellation for the implementation of full-duplex communication in communication systems via power circuits.

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