РАДІОЕЛЕКТРОНІКА

SWITCHING RIPPLE DATA TRANSFER TECHNIQUE USING STEP-DOWN DC-DC CONVERTER

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This paper describes an electronic communication method based on the use of the DC-DC converter as a data transfer device. Output voltage of a DC-DC converter is modulated with Amplitude-Shift Keying (ASK) signal carrier. Modulation takes place in the feedback loop of the DC-DC converter. The output signal passes through the transition line to the band pass filter, where unexpected noise and DC components are removed. Transition line is represented as a long wire with a certain length that contains active and reactive parasitic parameters. These parameters affect Total Harmonic Distortion (THD) of the initial ASK signal waveform. Switching ripple communications are introduced to simplify electrical connection and reduce the wire count. This makes it particularly suitable for Internet of Things (IoT) applications in challenging environments where RF may be weak or unreliable. Nowadays wiring is an expensive part of electronic products. Industry leading companies usually spend sufficient resources on wiring production and installation work. Switching ripple communication modules can reduce a final product price and increase reliability. Also, these systems can be easily implemented to existing designs because power line communication devices do not require additional signal pass conductors or additional RF modules for data transfer. The proposed communication method can be used in such industries as: battery management systems, industrial lightning control, automotive or even in high performance power supplies for telecom solutions. The purpose of this paper is to create a signal transfer model and show a dependency between transition wire length and total harmonic distortion parameter, which affects output signal. Low THD parameter is important for carrier signal decode operations. After the filtering stage ASK signal usually passes to the Microcontroller unit through the Analog to Digital converter (ADC) block. By increasing carrier signal THD the ADC effective number of bits (ENOB) parameter will be affected. As a result, all further signal processing stages such as digital filtering and calculations will take more hardware resources.

Keywords: *DC-DC, ASK, Feedback, Ripple, THD*

1. Introduction

The ripple parameter [1] in a DC-DC converter refers to the amount of voltage fluctuation present in the output voltage. It represents the deviation or variation of the output voltage from its average or nominal value. Almost impossible to avoid this parameter in today's DC-DC and AC-DC converters due to the cost and efficiency requirements. Other way it is possible to use ripple for data transfer between source and load devices. This method can be applied to any industry, where currently each block has both – power and data transfer wires. Switching ripple communications can be used to deal with such challenges for any industry as: weight and space constraints and reliability or durability requirements. Wiring complexity of

modern devices, it's not uncommon for there to be thousands of individual wires running throughout modern devices, connecting various components and systems. However, the exact number of wires can vary greatly depending on the specific device and its configuration.

Ripple in DCDCs is caused by various factors that usually take place from parasitic issues of active and reactive components[2]. DC-DC converters use a switching mechanism to regulate the output voltage. The rapid switching of the input voltage can lead to variations in the output, causing ripple. The inductor and capacitor in the converter circuit play pivotal roles. The inductor smooths out the current flow, while the capacitor helps stabilize the output voltage. However, their characteristics such as ESR and ESL can introduce ripple if not appropriately managed. Changes in the load connected to the converter affect its output. Higher loads demand more current, potentially causing increased ripple. Conversely, lower loads may lead to decreased ripple. The frequency at which the converter switches impact ripple. Higher switching frequencies typically result in lower ripple due to shorter intervals between switching cycles, allowing for more precise regulation. Conversely, lower switching frequencies may result in higher ripple due to longer intervals between switches. Understanding and managing these factors are essential for designing DC-DC converters with minimal ripple, ensuring stable and reliable power output for various applications. A low ripple parameter signifies minimal voltage fluctuation, indicating a more stable and reliable power output. On the other hand, a high ripple parameter indicates larger voltage fluctuations, which can lead to issues such as electromagnetic interference (EMI)[3] and reduced performance of sensitive electronic components.

In some scenarios, DC-DC converters are utilized to power communication systems or devices, like in wireless communication setups or RF transceivers. In these instances, ASK[4] modulation might be employed for wireless digital data transmission. Here, DC-DC converters ensure stable power levels for communication components, while ASK modulation encodes digital data onto carrier waves for transmission. However, the idea of switching ripple communications is to implement ASK modulator to DC-DCs feedback loop[5].

Feedback is essential for DC-DC converters, ensuring a stable output voltage and optimal performance.

DC-DC converters rely on feedback to adjust their operation and maintain the desired output voltage level. This involves comparing the actual output voltage with a reference voltage and making necessary adjustments. Typically, a portion of the output voltage is compared to a reference voltage using a voltage divider network. Any differences between the two voltages are used to adjust the converter's operation through a control circuit. There are different approaches to feedback control, such as voltage mode control and current mode control. Voltage mode control directly regulates the output voltage, while current mode control focuses on regulating the output current. Feedback enables rapid responses to sudden changes in load conditions, minimizing voltage fluctuations. In summary, feedback control is vital for maintaining stability, accuracy, and responsiveness in DC-DC converters, contributing to their reliability and efficiency.

2. Related Works

Ripple communication technique takes its essential roots from PLC. Paper[6] details the evolution of powerline communications (PLC) for managing power distribution grids. The first-generation ripple control systems provided one-way communication, which has been used for centralized load control and peak shaving for many years. The European standards body CENELEC limited the frequencies between 3 kHz and 95 kHz for two-way communications used by electricity distributors. In the 1990s, several low data rate second generation PLC systems were introduced, leading to the implementation of Automatic Meter Reading systems.

Visible light communication systems integrate LED lighting with wireless communication. Traditionally, power conversion and communication are designed separately, which allows for high bit

rates but increases costs and impacts efficiency due to the additional circuitry required for communication. Alternatively, power conversion and communication can be designed together using switching ripple communication (SRC), which eliminates the need for additional devices. However, SRC typically employs broadband modulation methods, resulting in bandwidths much lower than the switching frequency. Paper [7] proposes a novel VLC scheme that applies baseband modulation to SRC by leveraging information theory in pulse width modulation. This approach achieves a high bit rate with a relatively low switching frequency. Additionally, it decouples power control and communication, preventing them from influencing each other.

In the newly proposed wire communication system, converters are utilized both as transmitters and power supplies. Signal transmission is performed using the output voltage ripple. When transmitting a message, the ripple is intentionally increased and modulated by the signal. Paper [8] suggests altering the output filter capacitor of the DC-DC converter depending on whether it is in reception or transmission mode. During reception, the output voltage ripple is minimized. During transmission, the output voltage ripple is enlarged and used as a carrier signal. For a buck-type DC-DC converter with a small output capacitor, the output voltage ripple becomes almost sinusoidal when the duty ratio is 0.5. The output impedance is investigated from the perspective of impedance matching. The magnitude of the ripple voltage can vary due to several factors. Therefore, digital frequency modulation (FM), such as frequency-shift keying (FSK), is recommended for this application.

Distributed Power System is a widely adopted power structure for renewable energy applications, telecommunications, computer systems, the aerospace industry, and more. DPS offers greater reliability and flexibility compared to traditional concentrated power systems. Communication within DPS utilities is crucial for the system's framework, with reliability, low cost, and ease of implementation being key factors for the communication system. Paper[9] proposes an embedded power line communication scheme that uses switching ripple as the signal carrier and the power line as the communication channel. Combining power transmission and communication while ensuring they do not interfere with each other is challenging. The proposed solution includes a prototype featuring several Buck converters sharing a common bus. To achieve stable switching ripple at the input communication port, a one-turn coil coupled with the energy storage inductor is added. Frequency Shift Keying (FSK) modulation and Discrete Fourier Transformation (DFT) demodulation are employed to facilitate communication. The feasibility of the proposed communication scheme is verified through simulation and experimentation.

3. Modelling and Simulation

In general system can be described in several sequential blocks that take part in overall signal operations. The signal chain starts from the ASK signal source.
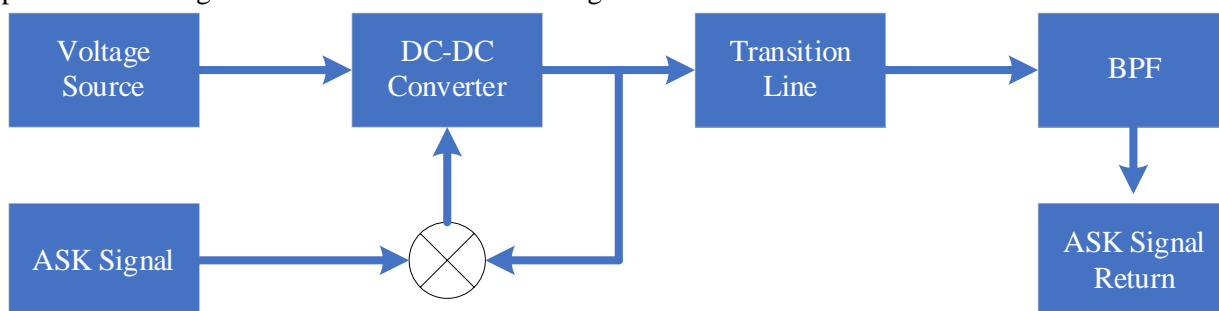

Fig. 1. General system block diagram

DC-DC regulator margining involves fine-tuning the output voltage of a linear voltage regulator to meet specific requirements across different operating conditions. It's a vital step in testing and validating electronic circuits to ensure they perform reliably. By adjusting the regulator's output voltage within a defined margin, engineers can simulate various scenarios and assess the system's ability to handle changes

in supply voltage, load conditions, and environmental factors. Figure 2 demonstrates an SRC host model, where "V6" is ASK signal source, connected to the feedback loop through "R4". Here the default application schematic for a DC-DC converter
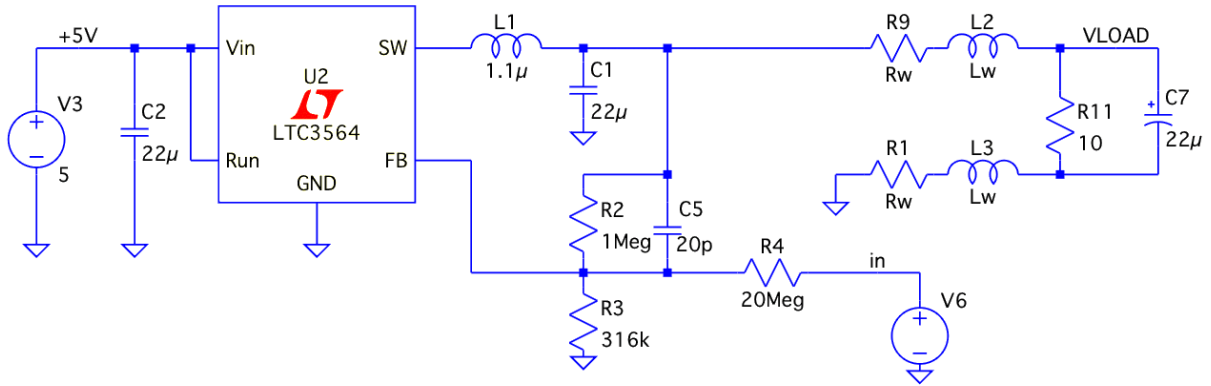

Fig. 2. SRC schematic approach

ASK signal waveform generated on "V6" can be described as:

$$s_{ASK}(t) = V_{OCM} + b(t) * c(t), \tag{1}$$

where $s_{ASK}(t)$ is a signal waveform function, $b(t)$ - binary message function, $c(t)$ - carrier signal waveform, V_{OCM} - DC offset voltage value.

$$b(t) = \begin{cases} \sqrt{Eb} & binary\_1 \\ \sqrt{Eb} * m & binary\_0 \end{cases}, \tag{2}$$

where $\sqrt{Eb}$ is energy, m is a modulation coefficient.

$$c(t) = \sqrt{\frac{2}{Tb}} \sin(2\pi f_c t) \tag{3}$$

where Tb is a unit energy over a single bit interval; f_c is a carrier signal frequency.

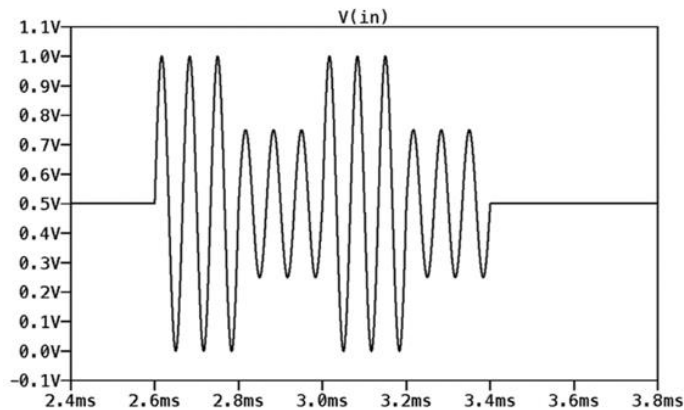Simulation result is demonstrated in Figure 3.

Fig. 3. Simulated ASK waveform. $V_{OCM} = 0.5V, f_c = 15kHz$

The output voltage for a DC-DC converter modulated by ASK signal $s_{ASK}(t)$ can be described as:

$$s_{dcdc}(t) = V_{ref} + \left(\left(\frac{V_{ref}}{R3} \right) + \left(\frac{V_{ref} - s_{ASK}(t)}{R4} \right) \right) * \frac{Z_{c5}R2}{Z_{c5} + R2}, \tag{4}$$

where V_{ref} is internal voltage reference value; $b(t) * c(t)$ is ASK signal waveform; Z_{c5} is capacitor impedance.

$$Z_{c5} = \frac{1}{j2\pi f_c C5} \tag{5}$$

Figure 4. shows output waveform generated by DCDC converter at the modulation time
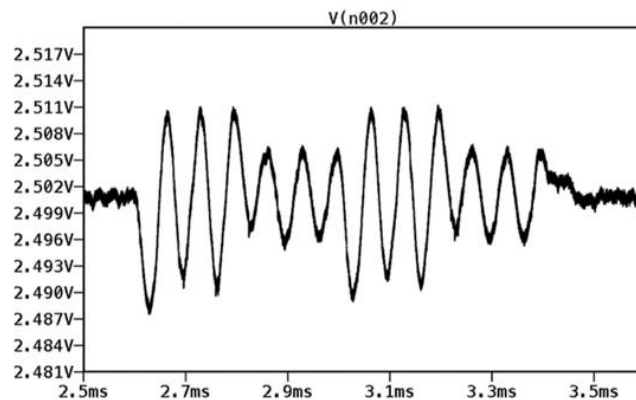

Fig. 4. Simulated DCDC output modulated by ASK waveform

A wire transmission line, also known as a transmission line, is a specialized cable or other structure designed to carry alternating current (AC) of radio frequency (RF) or, in some cases, direct current (DC) from one point to another. Transmission lines are essential components in a wide range of applications, including telecommunications, electrical power distribution, and radio frequency transmission. Transmission lines exhibit several parasitic characteristics that can affect their performance, especially at higher frequencies. These parasitic elements include resistance (R), inductance (L), capacitance (C), and conductance (G). Understanding these characteristics is crucial for designing and analyzing transmission lines in various applications. Figure XX demonstrates a transition line model with parasitic elements. R11 represents a DCDC load and C7 is a value of line device input capacitance
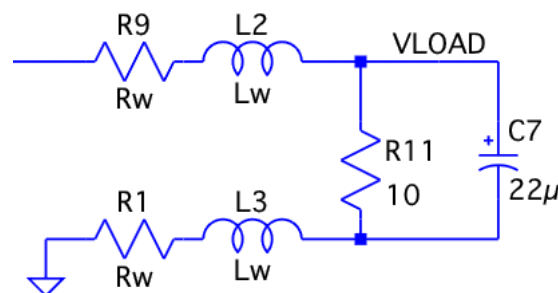

Fig. 5. Transition line approach

Inductance is the property of a conductor by which a change in current through it induces an electromotive force (EMF). It arises from the magnetic field generated by the alternating current flowing through the conductors. Inductance can cause signal distortion and phase shift, particularly at higher frequencies.

$$L = 2l\left\{\ln\left[\left(\frac{2l}{d}\right)\left(1 + \sqrt{1 + \left(\frac{d}{2l}\right)^2}\right)\right] - \sqrt{1 + \left(\frac{d}{2l}\right)^2} + \frac{\mu}{2} + \frac{d}{2l}\right\},\qquad(6)$$

where L - inductance of a straight wire in henries (H), d - diameter of the wire in cm, l - length of the wire cm, μ - permeability.

Resistance is the opposition to the flow of electric current, causing power dissipation in the form ofheat.Resistance is primarily due to the finite conductivity of the conductors and increases with length and decreases with the conductor's cross-sectional area. Higher resistance leads to greater signal attenuation and power loss.

$$R = \frac{\rho l}{\pi\left(\frac{d}{2}\right)^2},\qquad(7)$$

where ρ - is the Resistivity of the conductor in $\Omega.m$, l is the Length in meters, d is the diameter of the round conductor in meters. Table 1 shows calculation results for AWG 16 copper wire with d=1.29mm

Table 1

Relations between cable length, inductance and resistance

Length, m	L, µH (Lw)	R, mΩ (Rw)
1	1.46	13
2	3.19	26
3	5.03	39
4	6.94	52
5	8.9	65

Output waveform for overall system can be described as:

$$s_{dcdc}(t) = R9I(t) + L2\frac{dI(t)}{dt} + \frac{1}{R11C7}\int_0^t I(t)dt + L3\frac{dI(t)}{dt} + R1I(t)\qquad(8)$$

By solving this equation possible to get the output waveform on "VLOAD" net. A band-pass filter is an electronic circuit that allows signals within a specific frequency range to pass through while attenuating signals outside that range. This type of filter is essential in various applications, such as audio processing, radio communications, and signal processing, to isolate a particular band of frequencies.
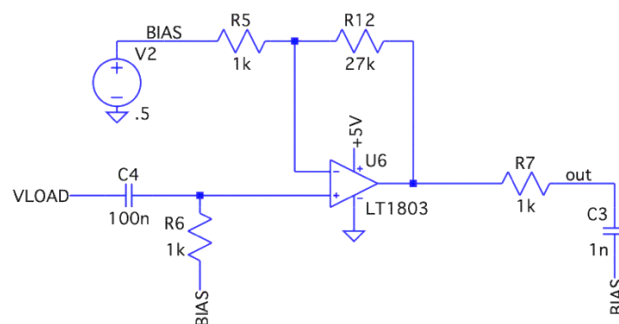

Fig. 6. BPF schematic

$$H(\omega) = \frac{R6}{R6 + Z_{c6}} * A_v * \frac{Z_{c3}}{R7 + Z_{c3}} \tag{9}$$

where A_v is gain value (V/V), Z_c is impedance, which calculated $Z_c = \frac{1}{j\omega C}$.

$$f_L = \frac{1}{2\pi R6C4} = 1591 \text{(Hz)}, \quad f_H = \frac{1}{2\pi R7C3} 159149 \text{(Hz)}, \quad f_0 = \sqrt{f_L f_H} = 15914 \text{ (Hz)},$$

$BW = f_H - f_L = 157558 \text{(Hz)}$, $Q = \frac{f_0}{BW} = 0.1$, where f_L is Low cutoff frequency, f_H is High cutoff frequency, f_0 is center frequency, BW is bandwidth, Q is the quality factor of the filter. For the given transfer function, the phase response can be derived and typically looks like:

$$\varphi(\omega) = \arctan\left(\frac{\omega}{\omega_0/Q} - \frac{\omega_0/Q}{\omega} \right) \tag{11}$$

where ω_0 is the center angular frequency, and calculated as $\omega_0 = 2\pi f_0$

Figure 7 demonstrates AC simulation result for a given bandpass filter with input "VLOAD" source with 1V amplitude.
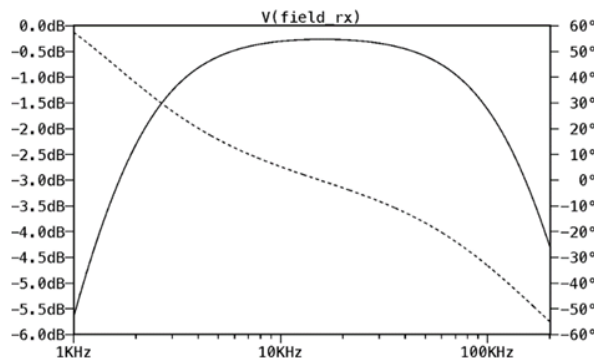

Fig. 7. Filter phase and frequency response

Harmonic distortion refers to a signal distortion that occurs when harmonics (integer multiples of the fundamental frequency) are added to the original signal. This phenomenon is common in various electronic systems, particularly in audio and communication systems, where it can affect signal quality and fidelity. In communication systems, harmonic distortion can interfere with the clarity and integrity of the transmitted signal.

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + V_6^2 + V_7^2 + V_8^2 + V_9^2}}{V_1}, \tag{12}$$

where V_1 is the RMS voltage of the fundamental frequency, $V_2, V_3, V_4, \ldots$ are the RMS voltages of the harmonics.

Harmonic distortion is a critical parameter in the performance of electronic systems, particularly in audio, communication, and power systems. Understanding its causes, effects, and methods to measure and mitigate it is essential for designing high-quality electronic circuits and systems. For THD calculation use a 15kHz as a first harmonic.

4. Modelling results and conclusion

This research proposed DC power line communication system approach using a high frequency buck converter with modulated feedback loop. Each signal transfer stage described by equations and had a visible simulation result.
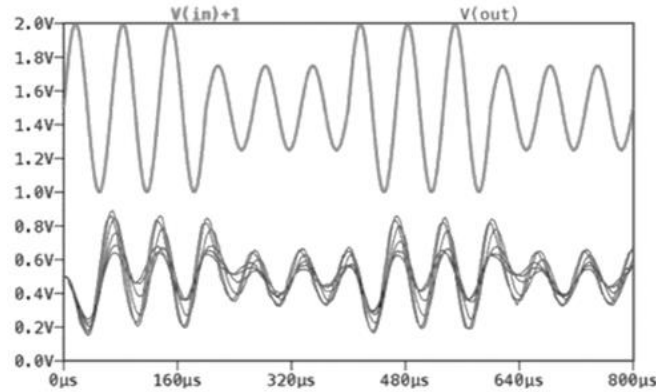

Fig. 8. Simulation results

Figure 8 demonstrates a simulation result corresponding to data points from Table 1. The upper waveform is an initial input ASK signal.
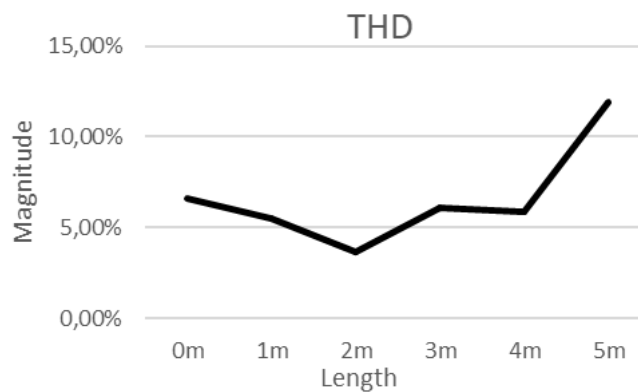

Fig. 9. Relation between transition line length and THD

Figure 9 shows that THD increases with a wire length. The optimal length for THD<6% is above 4 meters for AWG 16 cable. This paper aims to create a signal transfer model and show a dependency between transition wire length and total harmonic distortion that affects the output signal. A low THD parameter is important for carrier signal decode operations because this parameter will affect an ADC's effective number of bits[10].

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ТЕХНОЛІГІЯ ПЕРЕДАЧІ ДАНИХ ЗА ДОПОМОГОЮ ПУЛЬСАЦІЙ НА ОСНОВІ ІМПУЛЬСНОГО ПОНИЖУЮЧОГО ПЕРЕТВОРЮВАЧА

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У цій статті описується метод електронної комунікації, заснований на використанні перетворювача DC-DC як пристрою для передачі даних. Вихідна напруга імпульсного перетворювача постійного струму моделюється за допомогою сигналу амплітудної маніпуляції (ASK). Модуляція відбувається в колі зворотного зв'язку імпульсного перетворювача. Вихідний сигнал проходить через лінію передачі до смугового фільтра, де шуми та постійна складова відкидаються. Лінія передачі представлена у вигляді довгого провідника певної довжини, що містить активні та реактивні паразитні параметри. Ці параметри впливають на загальне спотворення гармонік (THD) початкової форми ASK сигналу. Метод передачі даних за допомогою пульсацій може бути використаним для спрощення електричного підключення та зменшення кількості провідників в системі. Це робить його особливо корисним для пристроїв Інтернету речей (IoT), які використовуються у нетипових середовищах, де радіочастотний сигнал може бути слабким або ненадійним. У наш час електричні кабелі є дорогою частиною електронних виробів. Великі компанії витрачають значні ресурси на виготовлення електропроводки та кабельні монтажні роботи. Використання модулів зв'язку на основі пульсацій може знизити кінцеву ціну продукту та підвищити надійність. Крім того, ці системи можуть бути легко вбудовані в існуючі пристрої, оскільки пристрої зв'язку на основі пульсацій не вимагають додаткових провідників або додаткових радіочастотних модулів для передачі інформації. Запропонований метод зв'язку може бути використаний у таких галузях, як: системи керування батареями, промислове керування освітленням, автомобільна промисловість або навіть у високоефективних джерелах живлення для телекомунікаційних рішень. Метою цієї роботи є створення моделі передачі сигналу та демонстрація залежності між довжиною провідника та коефіцієнтом нелінійних спотворень. Низький КНС важливий для операцій декодування та обробки сигналу. Після етапу фільтрації ASK сигнал через блок аналого-цифрового перетворювача (АЦП) проходить до мікропроцесора. Збільшення КНС сигналу вплине на значення ефективної кількості бітів АЦП (ENOB). В результаті, всі подальші етапи обробки сигналу, такі як цифрова фільтрація та обчислення, потребуватимуть більшої кількості апаратних ресурсів

Ключові слова: *імпульсний перетворювач, зворотній зв'язок, амплітудна модуляція, пульсації, THD.*