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Overcoming Methodological Limitations in Modeling Impulse Signals

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***Abstract* — The goal of this research is to advance methods for modelling impulse signals, thereby reinforcing the foundations of intelligent systems and enhancing engineering solutions for integrating next-generation technologies from the earliest design stages. The unresolved issue of dual definitions of electric power neglected until now and restricting the modelling of pulsed signals, is investigated here for the first time. Addressing this problem expands theoretical knowledge for practical engineering applications. Classical formulas for calculating the average power of DC sources produce systematic errors when applied to pulsed signals in circuit sections and lead to the emergence of anti-patterns in the algorithms of widely used software tools. To overcome these limitations, an additional formula for average power and a new modelling concept are proposed, which ensure accurate determination of power and energy in accordance with Ohm's law. By using rectangular pulses as reference waveforms, this approach enables reliable modelling of pulse signals with any time profiles and establishes a rigorous computational basis for future applications.**

Keywords — ideal source, duty cycle, pulse power, average power, circuit section, Ohm's law, algorithmic anti-patterns

I. INTRODUCTION

Historically, with the invention of the first direct current source, the galvanic cell, power-based analysis methods emerged and were later extended to harmonic currents as the following stage in electrical engineering. Advances in radio engineering, which first established the very concept of periodic and random analogue signals, enabled digital-pulse methods that underpin computing systems, telecom, radar, lidars, sonar, robotics, power electronics for renewable energy sources, and other modern systems. In general, power serves as a universal efficiency measure and an indicator of end-to-end coherence in energy and signal flows generation, transmission, reception, and processing, from the early stages of technologies and systems design (e.g., [1]).

However, traditional power analysis methods (e.g., [2]) remain rooted in engineering paradigms established before the widespread adoption of pulse-based technologies, which limiting advances in both hardware and software. A clear manifestation of these limitations is the systematic errors of software widely used in engineering practice and education, caused by anti-patterns of traditional methods in algorithms for calculating the average power [3–5].

To address this limitation, additional formula and more accurate model to refine the existing method are proposed. In this model, rectangular pulses serve as reference signals for analyzing voltage, current, power, and energy in pulses with arbitrary profiles under Ohm's law. In particular, this allows them to be directly mapped onto the input, logic, and output units of the FPGA, thus linking info flows with energy flows of their carriers – pulsed signals, within hardware.

II. ADDRESSING THE DUAL DEFINITION DILEMMA OF ELECTRIC CURRENT POWER

In physics, the power of an electric current (*P*), as with any other forms of energy in general, is defined as the rate at which energy (*E*) is expended to perform useful work or is converted into other forms over a given time period (*T*) [2]:

$$\Pi = E/T \Rightarrow E = \Pi \cdot T. \tag{1}$$

In engineering, direct-current power *P* is defined as the product of the fundamental physical quantities of voltage (*U*) and current (*I*) [2]:

$$\Pi = \Upsilon \cdot I. \tag{2}$$

In its generalized form, formula (2) is applied to calculate the instantaneous power ($p(t)$) of both analogue and discrete signals, expressed as the product of instantaneous voltage ($u(t)$) and current ($i(t)$) values:

$$\pi(\tau) = \upsilon(\tau) \cdot \iota(\tau). \tag{3}$$

Following the definition in (1), the signal energy is given by the integral of the instantaneous power values $p(t)$ over a period *T* [2]. From this, pulse power (P_i) and average power (P_{avg}) is derived. The conventional formula for calculating the average power of rectangular pulses is given below:

$$\Pi_{\alpha\varpi\gamma} = \Pi_\iota \cdot (\tau_\iota / T), \tag{4}$$

where t_i is the duration of the active phase of pulses.

Formula (4) is interpreted graphically in the relevant literature using the representation shown in Fig. 1, confer [6]. The ratio t_i/T, highlighted in colour by the authors in Fig. 1, is usually denoted by D and referred to as the duty cycle.

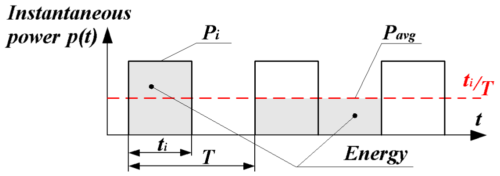

Fig. 1. Graphical representation of pulse power P_i and average power P_{avg} for a rectangular pulse in terms of $p(t)$, conventional in the literature.

A careful examination of expressions (1)–(4) reveals that the average power is not derived identically from definition (1) and from definitions (2)–(3). According to the second definition, it follows that:

$$\Pi_{\alpha\varpi\gamma} = Y_{\alpha\varpi\gamma}\cdot I_{\alpha\varpi\gamma}. \quad (5)$$

Equivalent transformations of equation (5) in accordance with Ohm's law produce the finalized formula, first proposed in [2], which differs from formula (4):

$$\Pi_{\alpha\varpi\gamma} = Y_{\alpha\varpi\gamma}\cdot I_{\alpha\varpi\gamma} =$$

$$= (Y_{\mu}\cdot(\tau_{\iota\square}/T))\cdot(I_{\mu}\cdot(\tau_{\iota\square}/T)) = Y_{\mu}\cdot I_{\mu}\cdot(\tau_{\iota\square}/T)^2 =$$

$$= (Y_{\mu}^2/P)\cdot(\tau_{\iota\square}/T)^2 = P\cdot I_{\mu}^2\cdot(\tau_{\iota\square}/T)^2 =$$

$$= \Pi_{\iota}\cdot(\tau_{\iota\square}/T)^2, \quad (6)$$

where U_m and I_m are the voltage and current amplitudes of the active phase of a rectangular pulse.

Unlike formula (4), formulas (6) and (2)–(3) demonstrate the relationship between power, voltage, and current within the framework of Ohm's law. In accordance with this law, a change in voltage across a section of a circuit causes an equal change in current. Consequently, a twofold change in voltage and current in formulas (2)–(3) yields a fourfold change in power. Also, a twofold change in the ratio t_i/T in formula (6) results in fourfold change in the average power. In particular, this is consistent with the scaling of energy that is carried by electromagnetic waves [7], as shown in Fig. 2.

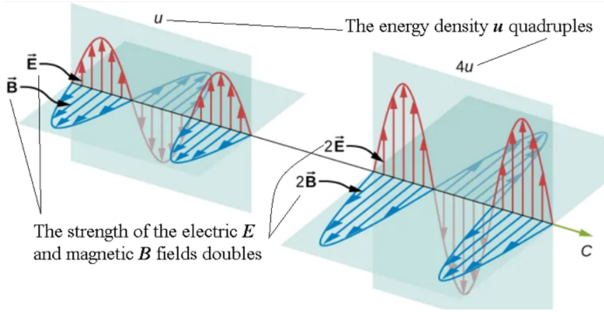

Fig. 2. Energy carried by a wave scales with amplitude: in electromagnetic waves, doubling the strength of fields E and B results in a quadrupling of energy density u and energy flux uc (adapted from [7]).

The discrepancy of formulas (4) and (6) stems from the dual definitions of power in formulas (1) and (2)–(3). Examination of the sources reveals that this duality remains unaddressed and may adversely affect practical outcomes.

Within this duality, formula (4) offers a comprehensive definition of power, making it ideal for calculating the total energy consumed from a source, especially when requiring a highly stable power supply.

Meanwhile, formula (6) is better suited to local analysis of circuit sections where the power of a time-varying signal is dissipated, since it expresses the instantaneous power.

The joint application of formulas (4) and (6) resolves the contradictions noted in [3–5]. This contributes not only to the end-to-end optimization of traditional systems but also to the advancement of next-generation technologies, such as [1], which require the alignment the power flows of direct current with harmonic and pulsed signals (Fig. 3).

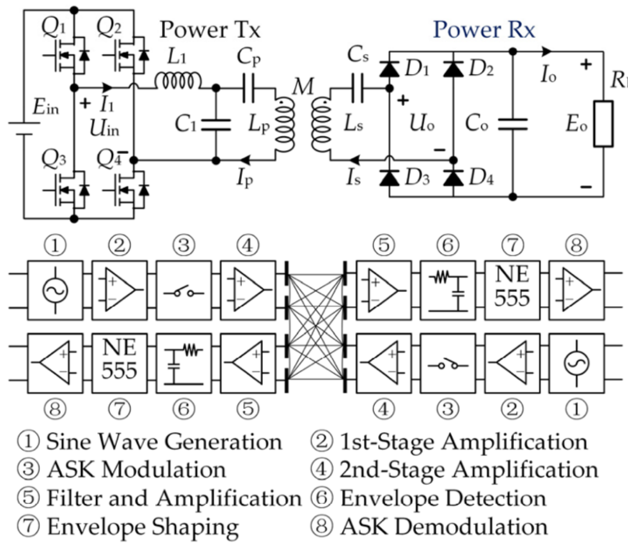

Fig. 3. Block diagram of hybrid electromagnetic field decoupled parallel transmission for power and signals (adapted from [1]).

III. THE "ENERGY BOX" CONCEPT FOR IMPULSE SIGNAL MODELING

Along with Equation (6), we introduce the concept of an "Energy Box", which provides an accurate representation of signal power and energy formation. This model fully adheres to definitions (1) and (2)–(3) within the framework of Ohm's law, encompasses all quantities essential for engineering calculations, and embodies the classical paradigm of energy-flow visualization, particularly as illustrated in Fig. 2.

Fig. 4 illustrates the application of the Energy Box model to a unipolar rectangular pulse, in accordance with formulas (4) and (6). In Fig. 4 (a), the pulse period is determined as $T=t_2-t_0$, while the active phase duration is given by $t_i=t_2-t_1$.

The instantaneous power in Fig. 4 (b) is shown as the area given by the product of voltage and current, e.g., at times t_1 and t_2. The pulse-energy in Fig. 4(c) is shown as the volume obtained by integrating instantaneous power over the pulse period T. This corresponds to formulas (1)–(6), given that the voltage, current, and energy of the pulse remain constant throughout the pulse duration t_i.

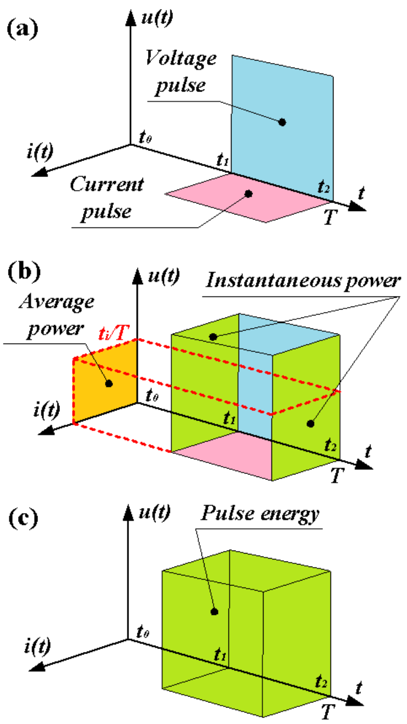

Fig. 4. Energy Box model, which describes the instantaneous power and energy formation of a source of unipolar rectangular current pulses.

The red dashed line in Fig. 4 (b) indicates the average power obtained with the t_i/T ratio according to formula (4). This offers a clearer illustration of the definitions in formulas (1)-(3) than the simplified representation in Fig. 1.

As evident from Figs. 4 (a)–(c), the definition in formula (1) refers to the power of the source, which must ensure a stable voltage or current regardless of the load resistance (R). This corresponds to the limiting behaviour of the source in accordance with Ohm's law as the load resistance R changes. The internal resistance of a real source (r) determines the limiting cases: if $r\to 0$, the source acts as an ideal voltage source ($U=const,\ R\to 0,\ I\to\infty$). If $r\to\infty$, it acts as an ideal current source ($I=const;\ R\to\infty,\ U\to\infty$). For these cases, formula (4) is accurate because averaging is performed for only one quantity – voltage or current – while the other quantity remains constant. This reduces the description of the power of the energy source to a single-variable function [3], which simplifies the calculation to the formula (4) and the graphical representation to what is shown in Fig. 1.

In particular, Fig. 4 (b) illustrates the case of the average power of an ideal current source, which is T/t_i times greater than the average power in Fig. 5 for a pulse signal on a circuit section, consistent with Ohm's law. This is defined from the equivalent direct current and voltage, which are T/t_i times smaller than the amplitudes of the current and voltage pulses, and equal to their average values.

Fig. 5 shows the Energy Box model applied to the DC voltage and current equivalent to the average values of the voltage and current for the pulse signal shown in Fig. 4(a). The instantaneous powers at times t_0 and t_2 in Fig. 5 (b) are equal to the average power according to formula (6) for the pulse in Fig. 4 (a). This average power are T/t_i times smaller than the average power in Fig. 4 (b) according to formula (4).

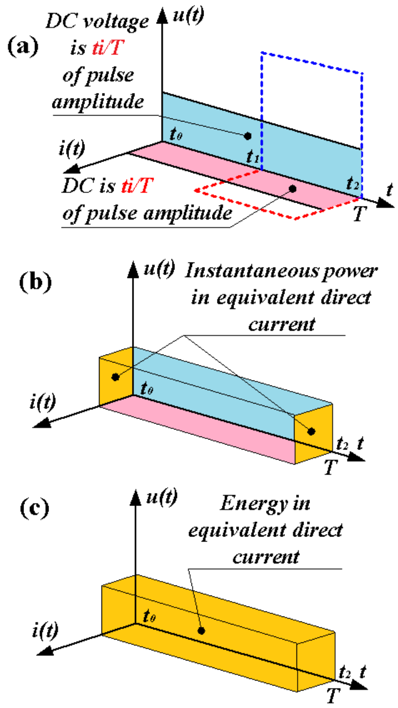

Fig. 5. Energy Box model, which describes the formation of instantaneous power and DC energy equivalent to a rectangular pulse signal.

A comparison of the models in Figs. 4 and 5 illustrates the origin of the dilemma that arises when considering power or as a function of a single variable (1), or as a composite function (2), without a careful examination of their practical context [3–5].

In addition, the Energy Box model provides a conceptual framework for the comprehensive modelling of pulse signals with arbitrary time profiles, employing rectangular pulses as a reference.

For example, Fig. 6 illustrates the traditional graphical-analytical representation of the average voltage and current values of continuous unipolar triangular pulses with different time profiles, constructed relative to the rectangular pulses (shown by the dotted line) with the same period T and duty cycle $D = t_i/T = ½$. These average values correspond to the height of a rectangle with area $S3$, identical to the areas of the triangular ($S2$) and rectangular ($S1$), amounting to ½ of the pulse amplitudes. Thus, their average power is identical, as they share the same average voltage and current.

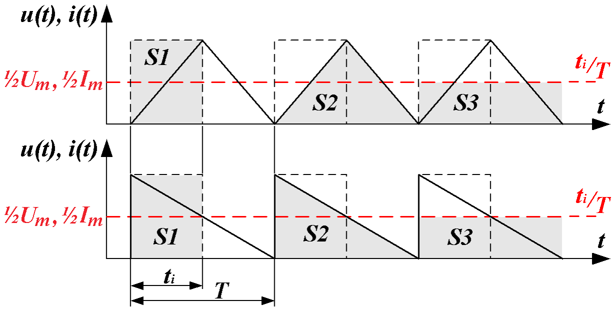

Fig. 6. Identical average voltage and current values for rectangular and continuous unipolar triangular pulses, based on the equivalence of areas *S1*, *S2* and *S3* and derived from their amplitudes.

However, the traditional representation in Fig. 6, like that in Fig. 1, does not provide an accurate and comprehensive understanding of how peak and average power and energy are interrelated and formed. In contrast, the Energy Box models in Figs. 7 and 8 offer a exhaustively complete and precise reflection of the relation between voltages, current, power, and energy in accordance with Ohm's law.

Manifestly, identical average voltage and current values in Figs. 8(a) imply identical instantaneous power in Fig. 8(b) and energy in Fig. 8(c) for the equivalent direct current.

IV. Conclusion

The average power of pulsed signals cannot be reliably determined from classical definitions without incorporating their duality within the framework of Ohm's law – a property inextricably embedded in formulations derived from both physical and engineering approaches. This unresolved issue has not yet been systematically addressed, and its resolution would not only advance existing theoretical foundations but also yield both technical and economic benefits for practical engineering, particularly through improved power alignment of FPGA architecture elements.

The proposed alternative formula for calculating average power, together with the comprehensive model that employs rectangular pulses as benchmark signals, provides a reliable basis for determining the parameters of signals with arbitrary waveforms. It is expected that further research leading to the creation of a universal method for modelling pulse signals.

Implementation of a system of formulas in accordance with Ohm's law for calculating the average power of energy sources and signals eliminates systematic errors in software tools widely used in engineering practice and education.

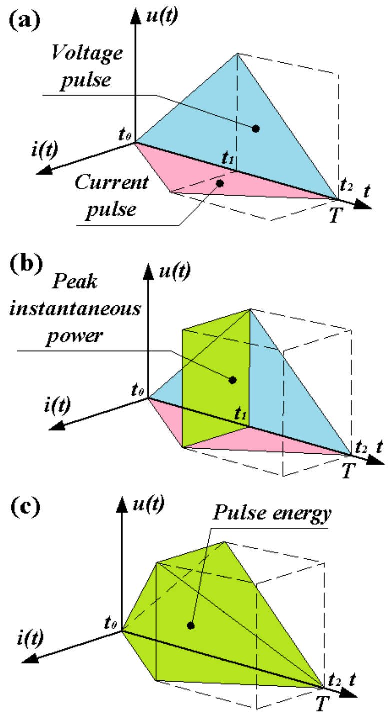

Fig. 7. Energy Box model, which describes the formation of instantaneous power and energy in continuous unipolar triangular pulses.

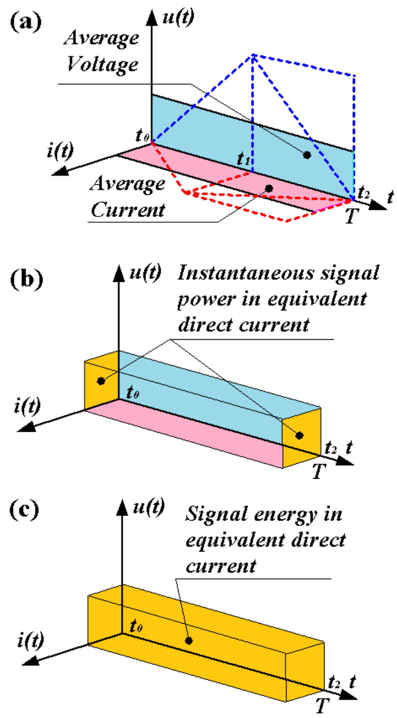

Fig. 8. Energy Box model illustrates the formation of the instantaneous power and energy of a signal in a circuit section according to Ohm's law, which are equivalent to direct current and correspond to the average values of voltage and current of the reference rectangular pulse (Figs. 4–5) and triangular pulse (Figs. 6–7).

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