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Finding the Harmonic Contents of Periodic Square Wave

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Abstract

This paper presents an analysis of the harmonic content in a periodic square wave. Three methods are employed to evaluate the harmonic characteristics: Fourier series decomposition, Crest Factor (CF), and Total Harmonic Distortion (THD). The Fourier series method decomposes the square wave signal into its direct current (DC) component, cosine, and sine terms. The second method, CF, is used as an initial indication of the presence of harmonics in the signal, where a CF value greater than 1 suggests a signal with harmonics. Finally, the THD method is utilized, which includes both the Fundamental THD (THDF) and the Root Mean Square THD (THDR), quantifying the degree of harmonic distortion in the signal. For the case studied, where the square wave has an amplitude of 1, the CF is found to be 1, the THDF is 46.1%, and the THDR is 41.9%. These results suggest that the square wave contains significant harmonic distortion. The paper highlights the importance of understanding harmonic content in power systems, particularly in the context of nonlinear loads that introduce distortion in voltage and current waveforms. The findings contribute to the broader understanding of harmonic effects on system performance, which can lead to issues such as overheating, protection malfunctions, and reduced power quality.

Keywords: Square wave, harmonic, Crest Factor, Total Harmonic Distortion

1. Introduction

The unrelenting proliferation of nonlinear loads in modern electrical networks has fundamentally challenged the traditional paradigm of pure sinusoidal power delivery. Contemporary power systems must accommodate an ever-increasing diversity of power-electronic devices—ranging from variable frequency drives and switching power supplies to consumer electronics and energy-efficient lighting systems—all of which introduce significant harmonic distortion into previously pristine 50 Hz or 60 Hz waveforms[1-3]. This shift has precipitated a cascade of power quality degradation issues that manifest as conductor overheating, equipment malfunction, protection coordination failures, and substantial economic losses throughout the electrical infrastructure.

Among the various non-sinusoidal waveforms encountered in power-electronic applications, the square wave emerges as a particularly instructive case study for understanding harmonic behavior and its systemic implications. Square waves, characterized by their abrupt transitions between fixed amplitude levels and equal positive and negative durations, represent one of the most severely distorted periodic signals encountered in practical systems[1],[4]. Recent research has demonstrated that square-wave inverters typically exhibit total harmonic distortion (THD) values approaching 48.3 percent, underscoring the critical importance of comprehensive harmonic analysis and mitigation strategies[5].

The mathematical foundation for understanding square-wave harmonics lies in Fourier series analysis, which reveals that these waveforms contain exclusively odd-order harmonic components whose amplitudes decay proportionally to the reciprocal of the harmonic order[1]. This characteristic harmonic spectrum, dominated by low-order components (3rd, 5th, 7th harmonics), poses unique challenges for power system design and equipment protection. The presence of triplen harmonics (multiples of three) introduces particularly problematic zero-sequence currents that accumulate arithmetically in neutral conductors rather than canceling, leading to dangerous overheating conditions[6-9].

Contemporary power quality standards, particularly IEEE 519-2014, establish rigorous limits for harmonic distortion to maintain system integrity and equipment longevity[10-13]. These standards recognize that harmonic distortion exceeding 5 percent voltage THD can compromise sensitive electronic equipment, while current distortion levels above recommended thresholds can precipitate transformer derating, cable failures, and nuisance tripping of protective devices[14-17]. The economic implications are substantial, with harmonic-related losses increasing quadratically with distortion levels and often necessitating oversized neutral conductors, specialized transformers, and sophisticated filtering systems[18].

Recent advances in harmonic mitigation have yielded an extensive arsenal of both passive and active technologies designed to restore power quality in harmonic-rich environments. Passive filtering solutions, utilizing carefully tuned inductor-capacitor combinations, provide cost-effective attenuation of specific harmonic frequencies but suffer from limited adaptability to varying load conditions[19], [20]. Active power filters represent a more sophisticated approach, employing real-time harmonic detection and cancellation through power-electronic injection of compensating currents[21], [22]. Additionally, multilevel inverter topologies have emerged as a promising solution for reducing harmonic content at the source through advanced modulation techniques and multiple DC voltage levels[23-25].

The integration of renewable energy systems has further complicated the harmonic landscape, as grid-connected inverters must simultaneously maintain power quality while accommodating variable energy sources[26]. Modern multilevel converter designs have demonstrated significant improvements in harmonic performance, with some configurations achieving THD reductions from conventional square-wave levels of 48 percent to acceptable values below 5 percent through sophisticated modulation strategies[27].

This paper aims to calculate the harmonic content of periodic square wave. There are three methods to apply here, the first one is the Fourier series to decompose square wave signal into its direct current value (DC, if any), cosine, and sine terms. The second method is Crest Factor (CF) as the first indication whether a signal contains harmonics or not. The last one is Total Harmonic Distortion in terms of fundamental (THDF) and Root Mean Square (RMS) values (THDR) of the signal.

2. Methods

2.1. Fourier Series (FS)

There are three methods we use here. The first methods we use is called Fourier Series[28]. This series can approximate a signal using only cosine and sine terms. The Fourier series is given by

$$f(\theta) = \frac{1}{2}a_0 + \sum_1^{\infty}(a_n \cos n\theta + b_n \sin n\theta) \tag{1}$$

where a_0 is a DC term, $\sum_1^{\infty} a_n \cos n\theta$ present if the signal is an even function, and $\sum_1^{\infty} b_n \sin n\theta$ present if the signal is an odd function.

The Equation (1) can also be defined as

$$f(\theta) = \sum_{-\infty}^{\infty} c_n e^{jn\theta} \tag{2}$$

The coefficients of a_0, a_n, and b_n are determined as follows

$$a_0 = \frac{1}{\pi}\int_{-\pi}^{\pi} f(\theta)d\theta \tag{3}$$

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(\theta)\cos n\theta \, d\theta \ \ (n \geq 0) \tag{4}$$

$$b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} f(\theta) \sin n\theta \, d\theta \quad (n \geq 1) \tag{5}$$

Using the above expressions, we get the Fourier series for the first five terms of periodic current square wave as

$$i(wt) = \frac{4I}{\pi}\sin wt + \frac{4I}{3\pi}\sin 3wt + \frac{4I}{5\pi}\sin 5wt + \frac{4I}{7\pi}\sin 7wt + \frac{4I}{9\pi}\sin 9wt + \cdots \tag{6}$$

Because square wave in this regard is an odd function, then all even harmonics are zero and only odd harmonics are present.

2.2. Crest Factor (CF)

The second methods we use is called CF and defined as

$$CF = \frac{peak\ value}{RMS\ value} \tag{7}$$

If the signal is pure sinusoidal then the $CF = \sqrt{2} = 1.414$. If a signal has CF > $\sqrt{2}$ then the signal tends to be sharp and if the signal has $CF < 2$ then the signal tends to be flat[29].

2.3. Total Harmonic Distortion (THD)

The third method is THD and expressed in percent[17]. There tow kinds of THD we use here, THD_F compared to fundamental value and THD_R

$$THD_F = \frac{\sqrt{H_3^2+H_5^2+H_7^2+H_9^2+H_{11}^2+H_{13}^2+H_{15}^2+H_{17}^2+H_{19}^2+H_{21}^2+H_{23}^2}}{H_1} \tag{8}$$

$$THD_R = \frac{\sqrt{H_3^2+H_5^2+H_7^2+H_9^2+H_{11}^2+H_{13}^2+H_{15}^2+H_{17}^2+H_{19}^2+H_{21}^2+H_{23}^2}}{\sqrt{H_1^2+H_3^2+H_5^2+H_7^2+H_9^2+H_{11}^2+H_{13}^2+H_{15}^2+H_{17}^2+H_{19}^2+H_{21}^2+H_{23}^2}} \tag{9}$$

The THD_R equation above can be written as $THD_R = \frac{THD_F}{\sqrt{1+THD_F}}$ (10)

compared to RMS value. The THD is given by equation.

3.Results and Discussion

3.1 Fourier Series Decomposition and Its Implications

The application of Fourier Series to approximate periodic signals, such as a square wave, is fundamental in signal processing and electrical engineering[28]. This mathematical technique effectively decomposes any periodic function into a sum of sines and cosines with different frequencies, representing the signal's harmonic content. The specific use of odd harmonics in the case of a square wave is accurate, as the square wave is an odd function, meaning it exhibits symmetry about the origin and contains no even harmonics.

While the mathematical formulation is correct, it is important to note that the convergence of Fourier series at points of discontinuity, such as the edges of a square wave, leads to the Gibbs phenomenon—an overshoot near the discontinuities that does not diminish even as more terms are added to the series[28]. This aspect could be briefly mentioned as a significant property when analyzing signals with sharp transitions, like square waves.

Additionally, in practical applications, higher-order harmonics may not always be accurately captured using the first few terms of the Fourier series. The total harmonic distortion (THD) and crest factor (CF), discussed later, are often used to measure the quality of signal reproduction when truncating the Fourier series, especially for signals like square waves that involve sharp transitions[14], [16], [29].

3.2 Crest Factor (CF): A Key Indicator of Signal Sharpness

The first indicator of harmonic content is *CF*. For the case of square waveform, where the peak value is 1 and the RMS value is also 1 then $CF = 1$. It could be seen that the CF smaller then $\sqrt{2}$ then the signal tends to be flat on **Figure 1**.

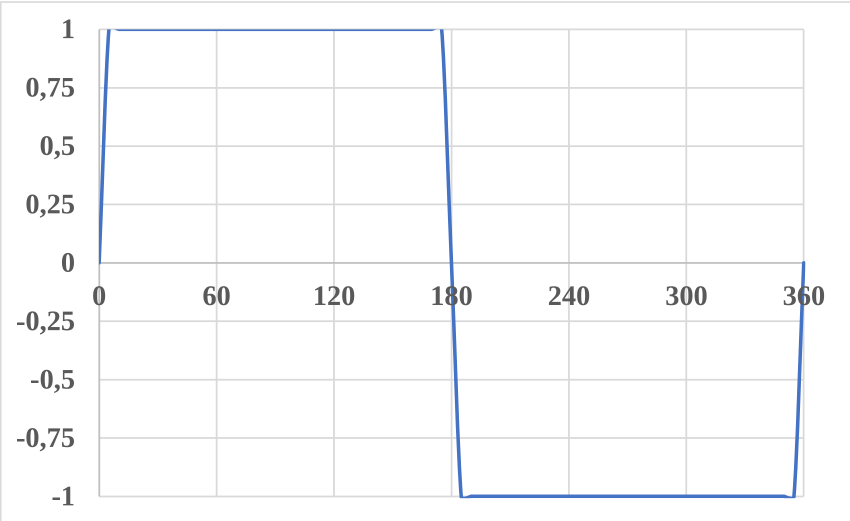

Figure 1. Square waveform.

Let $I = 1$ A, then the amplitude of the current harmonic for the first twelve terms is

$$A_1 = \frac{4 \times 1A}{\pi} = 1.273\ A$$

Remember that the value of A_1 is the fundamental value. The RMS value for the fundamental is $A_{1,RMS} = \frac{Peak}{\sqrt{2}} = \frac{1.273}{\sqrt{2}} = 0.900\ A$. It can be summarized all the other amplitude/peak value of the harmonic in **Table 1** and **Figure 2**.

The Crest Factor (CF) plays a vital role in assessing the sharpness of a signal[29]. As the paper rightly notes, a CF value greater than √2 indicates a signal with sharp transitions, while a CF less than √2 corresponds to a smoother signal. The CF for a square wave being exactly 1 is crucial, as it directly impacts how systems handle the signal in terms of voltage stresses and thermal effects.

In power systems or audio applications, a high CF indicates that the waveform contains significant peak values, which can lead to equipment stress, excessive heating, or increased power loss due to high peak currents[29]. This characteristic is critical in practical systems where these peaks can be detrimental to the efficiency of the system.

For example, in power supply systems, high CF values can lead to electromagnetic interference (EMI) due to sharp transitions in the waveform. In contrast, a smooth waveform with a CF near 1.414 (i.e., pure sine wave) is more efficient for power transmission, causing less interference and loss.

Tabel 1. value of the harmonic below

Harmonic	Peak (A)	RMS (A)	Peak^2
A_3	0.424	0.300	0.180
A_5	0.255	0.180	0.065
A_7	0.182	0.129	0.033
A_9	0.141	0.100	0.020
A_{11}	0.116	0.082	0.013
A_{13}	0.098	0.069	0.010
A_{15}	0.085	0.060	0.007
A_{17}	0.075	0.053	0.006
A_{19}	0.067	0.047	0.004
A_{21}	0.061	0.043	0.004
A_{23}	0.055	0.039	0.002
	Sum		0.587

3.3 Total Harmonic Distortion (THD): A Measure of Signal Integrity

Total Harmonic Distortion (THD), both as a ratio of the harmonic components to the fundamental frequency (THDF) and the ratio to the total signal (THDR), is a key metric in evaluating the integrity of a signal[16]. This paper clearly presents the formulas for these calculations, which are essential for understanding the influence of harmonics on signal quality. The THD_F is $\frac{0.587}{1.273} = 0.461$ or 46.1%, meanwhile the THD_R value is $\frac{THD_F}{\sqrt{1+THD_F^2}} = \frac{0.461}{\sqrt{1+0.461^2}} = 0.419$ or 41.9%.

The THDF calculated for the first 23 harmonics (46.1%) and THDR (41.9%) provide valuable insights into the signal's harmonic content. In real-world applications, the THD is used to quantify how much distortion is present in the signal relative to the fundamental frequency, which is crucial for applications requiring precise waveform reproduction[14].

For example, in audio systems, high THD values can introduce unwanted distortion, leading to a degradation in sound quality. Similarly, in power distribution systems, high THD values can result in inefficiencies and harmonic-related failures in equipment like transformers, motors, and generators. Systems that produce square waves or similar non-sinusoidal signals typically exhibit higher THD, making it essential to use filtering techniques to reduce these harmonics and improve overall performance.

3.4 Harmonic Spectrum Analysis

The harmonic spectrum analysis in **Figure 2** provides a clear visual representation of the harmonic content of the square wave. However, to enhance the analysis, the graph could be further enriched by including the frequency scale and emphasizing the decay of higher-order harmonics. The absence of even harmonics, as shown in the plot, confirms that the square wave is an odd function, but the influence of higher-order harmonics on the overall waveform could be discussed further.

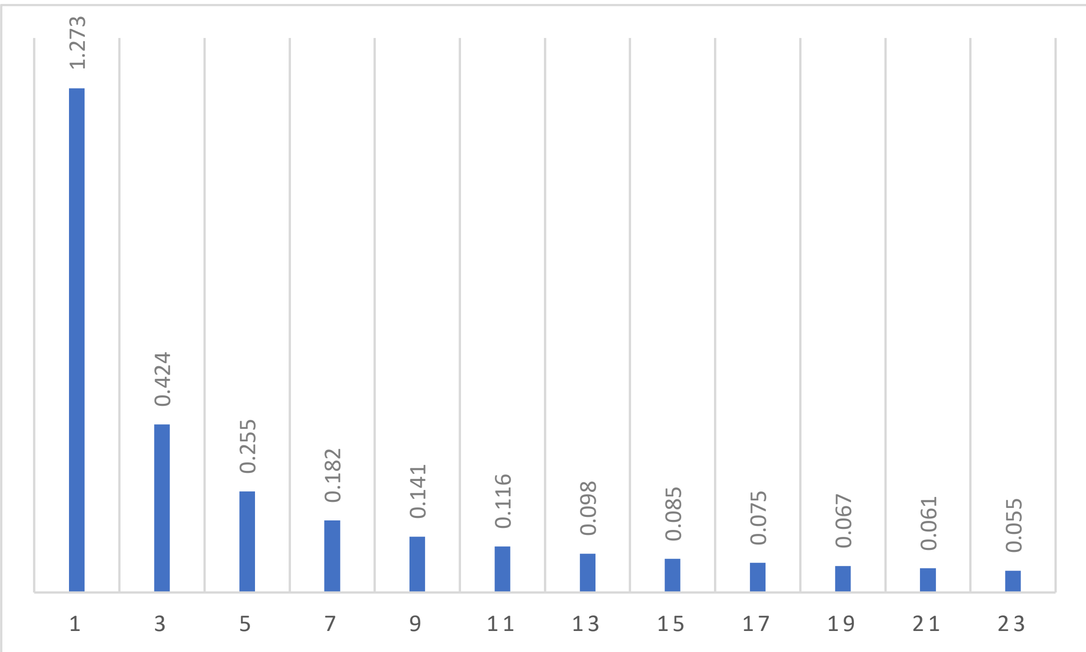

Figure 2. Frequency spectrum of harmonic

In addition, a comparison with other waveforms, such as a triangle wave or sine wave, would provide more context for the observed harmonics. This comparison could demonstrate the practical difference in THD values and CF between common waveform shapes and highlight how Fourier series analysis helps in identifying the best waveform for specific applications, such as power distribution, audio processing, or signal transmission[16], [29].

3.5 Practical Implications of Harmonics in Power Systems

Harmonic distortion is a significant concern in power systems and various electrical applications, and its impact goes beyond the theoretical calculations of THD and CF. High harmonic content in signals, particularly in the form of odd harmonics, can cause substantial practical problems in real-world systems[14]. These issues include transformer overheating, motor inefficiencies, and the possibility of resonance in circuits, which can cause equipment damage or system instability.

In transformers, for example, harmonic currents generate additional eddy currents in the core, increasing the heat dissipation, which reduces the efficiency and lifespan of the equipment[30]. The presence of harmonics in motors also leads to increased losses and a decrease in operational efficiency, requiring more power to achieve the same output. Furthermore, harmonic distortion can lead to the creation of resonance conditions, where certain harmonic frequencies cause the system to oscillate at dangerously high levels, potentially damaging components or destabilizing the entire system.

To address these challenges, engineers often use filtering techniques such as passive filters or active filters to mitigate harmonic content. These filters are designed to either block or attenuate the specific harmonic frequencies, ensuring that only the desired frequencies (typically the fundamental frequency) are present in the system. This is especially important in power distribution systems to prevent equipment failures and reduce operational costs.

Moreover, harmonics play a critical role in audio applications as well. High THD values in audio systems lead to distortion, which can severely affect sound quality. In this context, harmonic distortion is typically unwanted, and designers often use high-quality sine wave inverters or linear amplifiers to ensure clean signal reproduction.

4. Conclusion

This paper provides a comprehensive analysis of the harmonic content in a square wave, using Fourier series decomposition, Crest Factor (CF), and Total Harmonic Distortion (THD) as key methods to evaluate harmonic behavior. The results demonstrate that square waves, which contain significant harmonic distortion, present a notable challenge in power systems and audio applications. The CF and THD values suggest that square waves, with their inherent odd harmonics, can induce detrimental effects such as overheating, inefficiencies, and equipment malfunctions. This study underscores the importance of understanding and mitigating harmonic distortion, particularly in systems with nonlinear loads. As harmonic content becomes increasingly prevalent with the rise of power-electronic devices, adopting filtering solutions and advanced modulation techniques is critical to maintaining power quality and ensuring the longevity of electrical infrastructure. The findings of this research contribute to the broader understanding of harmonic effects and offer valuable insights into the design of systems capable of handling such distortions effectively.

Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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