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OPTIMIZING THE PERFORMANCE OF RMS MEASUREMENT ALGORITHM USING GAUSSIAN FILTER

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ABSTRACT

Root mean square (RMS) values must be measured precisely in the present era in order to improve the performance precision and high dependability of wireless communication equipment. The usual method of measuring RMS, which involves calculating the average of the squares of the input signal samples, has been the subject of numerous research articles. However, there are certain disadvantages to this approach, particularly when working with harmonic signals. In this paper, three formulas are proposed to estimate the systematic error in RMS measurement to contribute to solving this problem. The proposed formulas take a new approach and demonstrate the effect of the number of input signal samples and the type of domain used (time or frequency) on measurement accuracy. To demonstrate this change, graphs were created using MATLAB simulation. In this paper, the Gaussian window was tested in both the time and frequency domains, and the study demonstrated that the RMS error can be significantly reduced if the correct parameter is chosen and a suitable sample size is used for both domains. At an SNR of 30 dB, the impact of sample size on the outcomes is also described. When the simulation parameters were set to Fc/Fs = 0.25, the MEE findings were (0.00029, 0.000016, and 0.0000054) for sample sizes of 16, 32, and 64, respectively. The results obtained in this paper demonstrate the importance of selecting appropriate parameters for each application, confirming and enhancing the applicability of this research in most applications to support the high performance, high accuracy, and reliability of modern wireless communication devices. Several techniques and methods in this field have been reviewed, and the current RMS evaluation error was found to be approximately 10^{-4} (Sean Reiter and Stephen W. 2024), while the methodology proposed in this paper produces lower errors of approximately 10^{-5}.

KEYWORDS

Error estimation; Methodological error; Harmonic signal; Gauss window, RMS.

1. INTRODUCTION

In recent decades, there has been significant interest in studies on wireless communication systems and their applications. In particular, root mean square (RMS) evaluation has witnessed significant development because it plays a fundamental role in measuring effective voltage, which is used in harmonic signal analysis. Studies have shown that harmonics are bound to distort the waveform, but their contribution to power can be estimated from the RMS value (Andria and et al., 1989). (Sean Reiter and Steffen W. 2024) presented a good theoretical study to help reduce the evaluation error using only frequency domain Hermite interpolation. However, this design is difficult to implement in practice because it is complex and requires a large number of linear outputs to implement reduced-order models. The authors have demonstrated in several studies that the use of technical interpolation conditions and the Hermite approach allows for a better approximation of system dynamics. The results obtained from applying the proposed algorithms in this paper demonstrate that they offer better performance than existing traditional approaches because they produce lower evaluation errors for the RMS. Despite the significant advantages of scientific applications, especially modern ones, researchers face some challenges, which sometimes impose computational complexity and resource consumption during methodological and simulation development.

One of the most significant challenges is the difficulty of numerical integration. A new approach was proposed by (Marina Bulat et al. 2024) that focused on the Modified Simpson's 1/3 rule and the Modified Simpson's 3/8 rule. This study is considered a basic and important approach that is applied when the number of samples is small for each period of the signal to calculate the RMS. The traditional 1/3 and 3/8 Simpson's rules have some limitations, including the difficulty of obtaining satisfactory results when the number of samples is large. Applications and situations where there are few samples and the sampling frequency is low in relation to the fundamental frequency of the signal are handled by this rule. The theoretical conclusions are often supported by published scientific data in recent works on RMS estimation. These limitations reduce the flexibility of this technique because it is considered limited when working with techniques that require a large number of samples, making it less flexible than other integration techniques.

Researchers have proposed several different techniques for measuring RMS voltage. (Alrubei and Pozdnyakov, 2023) presented the following formula for analyzing RMS:

$$V'_{RMS} = \sqrt{\frac{1}{Tm}\int_0^{Tm} X^2(n)dt}\,, \tag{1}$$

where Tm is the measurement time, X(n) is the input signal, and V'_{RMS} is the observed value of RMS.

According to (Alrubei and et al., 2023), the connection between peak voltage Am and RMS voltage VRMS for sinusoidal waveforms is as follows:

$$V_{RMS} = \frac{Am}{\sqrt{2}}, \tag{2}$$

In general, there are two main types of RMS measurement: the first is in the time domain, and the second is in the domain of the frequency. The first method includes several techniques, some of which are indirect and involve approximating discrete input signal samples, including the input square filtering technique and the input derivative technique. The second method also includes several techniques, including quadrature demodulation and the discrete Fourier transform (DFT). All of these techniques are effective in measuring multiharmonic signals if appropriate transform parameters, windows, and simulations are set (M. Novotny et al., 2008; Duda and Krzysztof, 2011; Chen and Hong et al., 2011). However, no method or technique is free of limitations.

Among the most significant problems and challenges facing current methods and techniques are the impact of harmonics on measurement accuracy and the high sensitivity to small changes in the input signal. Furthermore, current techniques are highly sensitive to noise, making them particularly sensitive to noise when operating in a noisy environment. The selection of the correct method and optimal technique depends on the characteristics of the specific application and the signal characteristics. Appropriate parameters must be selected for each application. (H. Hegeduš, et al., 2011; Belega, D.and Petri, D. 2014).

Studies have shown that evaluation techniques based on zero-crossings or extreme thresholds suffer from several drawbacks. These include: Sometimes zero-crossings are completely absent; if used, The ratio of the signal's variable to constant components has restrictions. Current studies and simulations indicate that if the initial. The signal's phase is unpredictable. meter, the zero-crossing period must be limited to approximately 1.5 periods.

Sometimes inaccurate results are obtained when there are extreme values within the time period under consideration, as studies have shown: (Lin, Hsiung-Cheng, 2017; Ye, G., et al., 2014).

From the above, we conclude that traditional methods that rely on individual signal values, such as zero-crossings or extreme values, are ineffective in determining the period, especially when dealing with complex, non-sinusoidal signals. Therefore, more sophisticated, more accurate, less complex, and less error-prone strategies and procedures that consider a set of samples must be used.

In fact, the method and approach proposed by (Suhanova et al., 2020) are interesting because they identify important and good options for decreasing the RMS measurement error and building an output filter with minimal implementation complexity to an acceptable level. This method has some drawbacks, including the introduction of measurement errors when deviations in the input signal frequency are present, and additional errors when the input signal spectrum contains harmonics. This directly impacts measurement accuracy.

Among other important studies, (Coelho et al., 2021) presented a study in which they used the SDWT and SDWPT algorithms to estimate RMS values in different frequency ranges. This study has demonstrated the effectiveness of these two algorithms in analyzing the signal spectrum, but they suffer from some drawbacks, such as sensitivity to signal fluctuations.

One of the important studies presented by (Ido Amiel et al., 2022) in which an effective technique was used and proposed to evaluate the RMS, in which the researcher relied on approximating the instantaneous waveform employing harmonics and correction factors to determine values that facilitate the signal and data analysis processes by dividing signals that contain noise and interference into smaller parts. Some drawbacks of this method include the significant effort and labor involved in using correction factors due to potential distortions and inaccuracies, which requires prior adjustment of the parameters and parameters used.

Studies have shown that RMS fluctuations in many applications, including in the electrical grid, are inherently random. Therefore, real-time monitoring of the signal period is essential to correct the sampling period (De Souza et al., 2023). (Kuwałek et al,. 2024) presented a method for measuring the mean square root of periodic signals, where he was able to determine the period of the signal from the sum of the signal values, relying on the basic property of definite integration. One of the reasons and drawbacks that led to the lack of widespread use of this method is the very long processing time for the instantaneous values obtained.

All these challenges were taken into consideration, and a new method was developed to overcome most of them. This method uses the Gaussian time window, which is considered a promising approach in the field of RMS evaluation in the modern era. Particularly when approaching the frequency spectrum's center of gravity at the operational frequency, we demonstrated a method with good accuracy. In this piece, we'll talk about processing time. The suggested approach depends on shifting the Gaussian filter's primary parameters, like $\alpha = 8$ and $\delta = 2.5$, to find the signal period with the smallest value variations.

The method was tested through simulations with sample values of $N = 16$, 32, and 64, respectively.

The mean error estimate (MEE) values were only 0.00029, 0.000016, and 0.0000054.

With these results, the proposed method outperforms existing conventional methods.

The most important contributions of this article are:

• Time and frequency domain RMS estimation with and without a windowing function.

• The suggestion of a Gauss window-based, optimal method for calculating the RMS through non-coherent sampling.

2. RMS MEASUREMENT IN THE TIME DOMAIN

First, explain how to estimate the RMS without using a window. Formula (2) allows us to determine the true value of V_RMS. Formula (1) demonstrates that the RMS of analog signals can be evaluated. The measurement time is usually represented as:

$T_M = (Kp + \lambda).T_{sig}$, where T_{sig} is the signal period, λ is the decimal part of the last sample period where $0 \leq \lambda < 1$, and Kp is the number of integer periods in the sample.

For digital signals, we can use the equation shown in Formula (3) to estimate the RMS

$$V'_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2\ (n)}, \tag{3}$$

Where N is the number of samples.

The RMS mean error estimate (MEE) can be calculated using the following formula:

$$\delta_{RMS} = \frac{V'_{RMS} - V_{RMS}}{V_{RMS}}, \tag{4}$$

3. PROPOSED ALGORITHM IN TIME DOMAIN

Based on variations in the input signal spectrum, a novel method for calculating the RMS values of signals with changeable values has been put forth.

The windowing was used in the time domain, which naturally reduced spectrum leakage and improved measurement accuracy. The Gaussian window coefficients can be computed using the following formula (Kuwałek, Piotr, 2024):

$$w(n) = e^{\frac{-1}{2}\left(\alpha\frac{n}{\frac{N-1}{2}}\right)^2} = e^{-\frac{n^2}{2\delta^2}}, \tag{5}$$

Where: δ is a Gaussian random variable, and $(N - 1)/2 \leq n \leq (N - 1)/2\ \alpha$. A Gaussian probability density function's standard deviation is exactly equal to :

$$\delta = (N - 1)/(2\alpha). \tag{6}$$

It is commonly known that the window width and the value of α are inversely correlated. The larger the window, the higher the value of α. α has a default value of 2.5.

The following formula can be used to determine the window and coherent's RMS value:

$$V'_{RMS} = \sqrt{\frac{1}{N}\sum_{n=0}^{N-1}(w(n)\cdot x(n))^2}, \tag{7}$$

where x (n) is input samples, V'_{RMS} an estimate of the RMS. The suggested method for evaluating RMS in the time domain involves the sequential execution of the following steps:

Necessary parameters for simulation:

Rf=(1000-4000) Hz,

Fs= 10000 Hz,

duration= Fc/Fs *N,

N= 16, 32, 64 samples,

Fc/Fs = 0.1-0.4,

S/N= 30 dB,

A= 1, and initial phase of the signal = 0.

An analog signal is created using:

$$x(t) = A\,sin(2\pi Fc\;t + \varphi) \tag{8}$$

The following formula can be used to convert an analog signal into a digital signal using an ADC:

$$x(n) = \; A\,sin\left(2\pi\;n\;\frac{F_c}{F_s} + \theta\right) \tag{9}$$

Calculating the RMS true and estimated value using the following formula yields the correction factor K :

$$\text{K}= V_{RMS}/V'_{RMS} \tag{10}$$

The sample size and window type determine the value of K; for instance, for a Gauss window with N=16, the value is 1.5; for a window with N=32, it is 1.9; and for a window with N=64, it is 10.6.

The RMS and MEE are estimated using the methods in Equations 3 and 4, which were explained earlier. The error plots and error data matrix are then generated using simulation and the proposed method.

4. PROPOSED ALGORITHM IN FREQUENCY DOMAIN

It is well-known and widely accepted in most research sources that the accuracy of the Fast Fourier Transform (FFT) algorithm can determine and measure RMS uncertainty in the frequency domain. To obtain V_{RMS}, the instantaneous values are sampled at the same sampling frequency and at the same time interval T/N, summed, and divided by N.

$$V_{RMS} = \sqrt{\sum_{i=1}^{N} u_i^2} \tag{11}$$

The algorithm and its proposed steps in this article are illustrated in Fig.1 : Determine the signal's RMS: just the first harmonic; all of the operational frequency band's harmonics;

within a specified bandwidth:

$$V_{RMS} = k/\sqrt{2}\sqrt{\sum_{N1-d}^{N1+d} S_i^2} \tag{12}$$

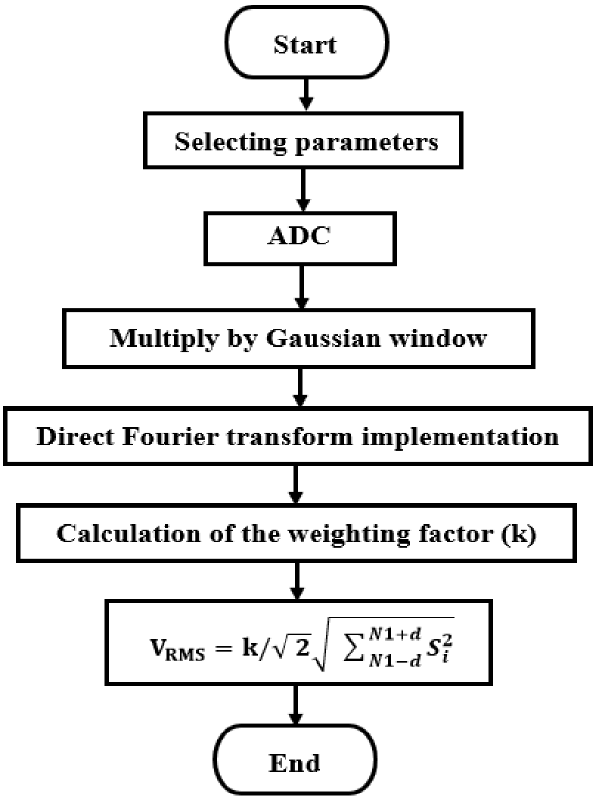

Fig. 1. Procedure of the general estimation RMS method

where Si represents the spectral component amplitudes, N1+d is the number of spectral components that correspond to the signal's first harmonic position, d is the number of spectral components that account for spreading. It is worth noting that combining DFT with finite impulse response (FIR) filters provides important advantages, such as highly efficient signal analysis and high-accuracy RMS calculations, provided the time windowing technique is used (L. Xu, et al., 2020; Kuwalek, Piotr, 2020; Coelho, Rodrigo de Almeida, and Núbia Silva Dantas Brito, 2021).

5. RESULT AND DISCUSSION

The findings are shown in this section without windowing, then results of the proposed algorithm with windowing in time and frequency domain To produce charts of the RMS estimate's MEE as a function of the signal frequency to discretization frequency ratio, we utilize MATLAB 2016 as our simulation package. This will allow gaining a more complete understanding of the signal behavior and its characteristics both in time and in the frequency domain. This approach allows studying the properties of signals in depth and better understand their structure.

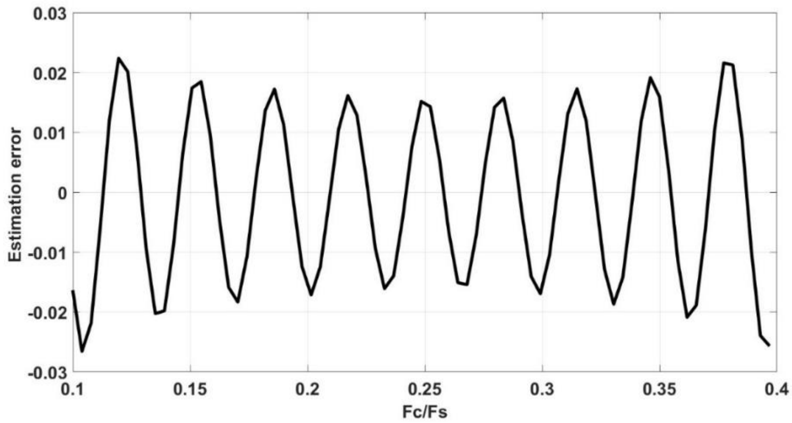

Fig. 2. RMS estimation in the time domain at N=16.

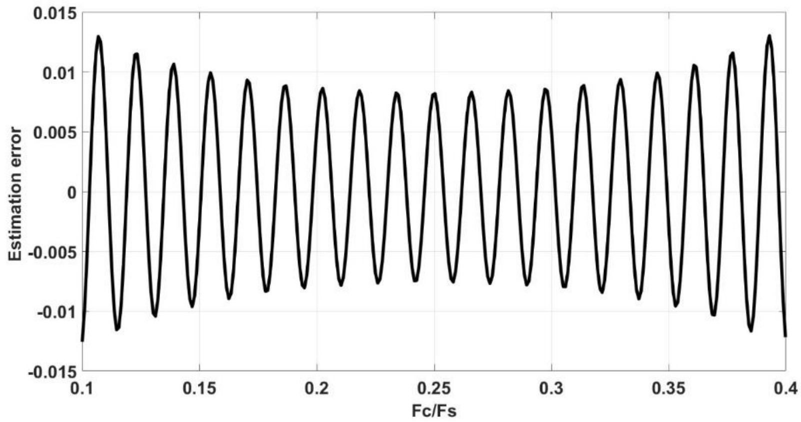

Fig. 3. RMS estimation in the time domain at N=32.

Here, the calculations of the evaluation errors at each frequency in the time domain without windows were performed. In this modeling, the results were obtained by applying Formula (2). In Fig. 2-4, the results of the mathematical modeling are presented as graphs for different sample sizes, 16, 32, and 64, respectively.

The RMS estimate in Fig. 2-4 has maximum MEE values of 0.022, 0.012, and 0.006 within the operational frequency range. This is typically the case, though, for small values of k and a small number of signal harmonics.

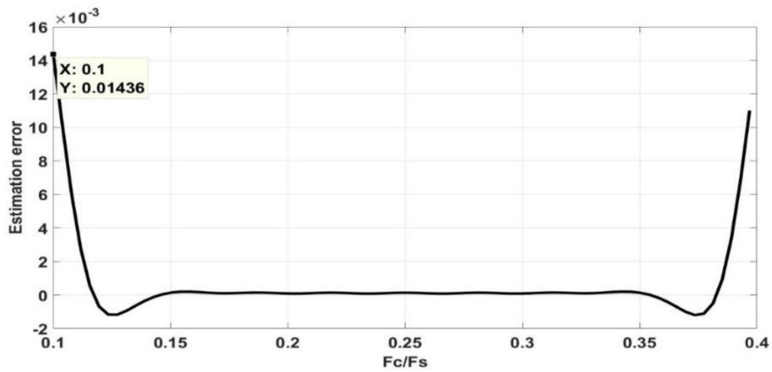

Fig. 4. RMS estimation in the time domain at N=64.

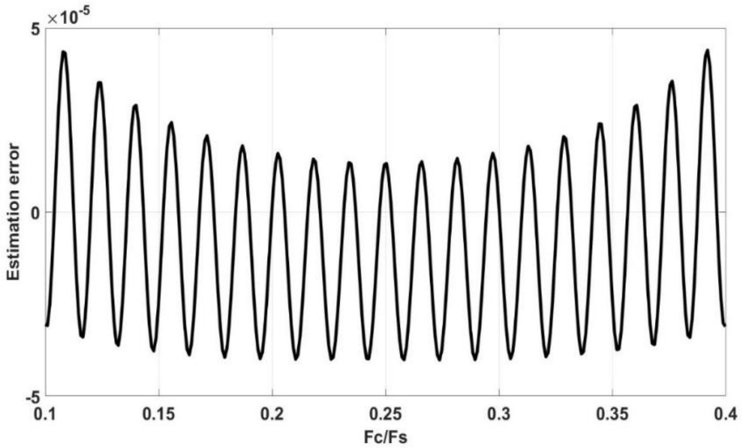

Fig. 5. RMS estimation in the time domain with Gauss window at N=16.

After implementing the Gaussian window, Fig. 5 to 7 illustrate the calculation of the mean error evaluation (MEE) of the RMS value. The graphs show the maximum errors in the time domain for different sample sizes: 16, 32, and 64 samples. The graphs show a significant reduction in the evaluation error compared to the algorithm previously implemented without a Gaussian window. The error dropped to 0.014 at a sample size of 16. Meanwhile, the error dropped significantly at a sample size of 32, reaching 0.00004. When applying the 64-sample model, the error was cut in half compared to the 32-sample model, reaching only 0.00002.

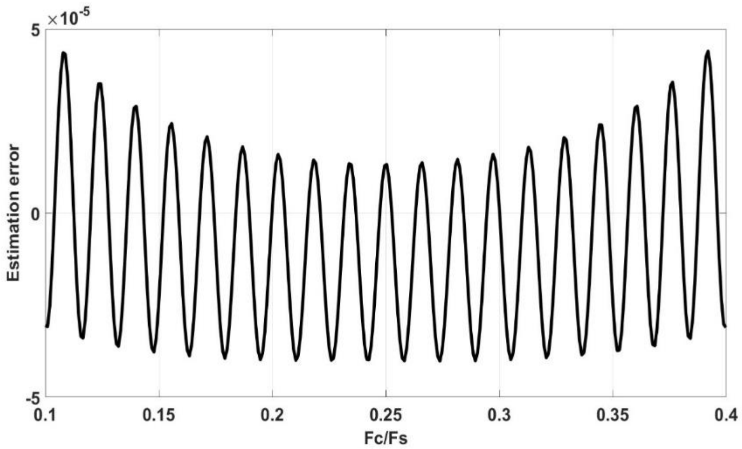

Fig. 6. RMS estimation in the time domain with Gauss window at N=32.

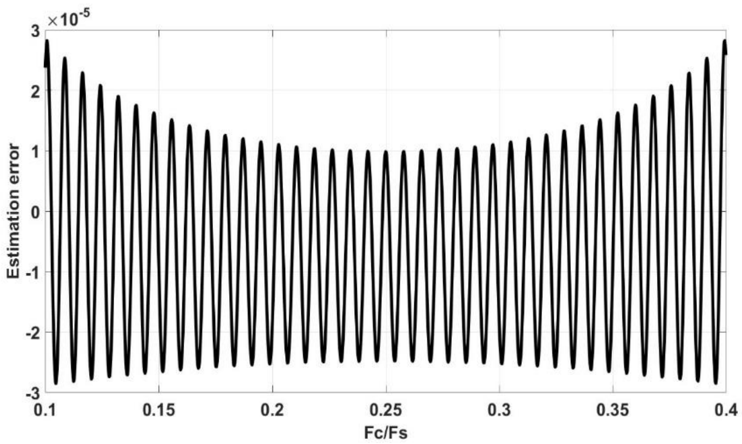

Fig. 7. RMS estimation in the time domain with Gauss window at N=64.

The Gauss window is using for the RMS measurements in the frequency domain in the second portion of the simulations. For N=16, 32, and 64, respectively, the ideal values are k = 1.53397982, 1.632993162, and 1.586302719. For a Gaussian window, the MEE graphs used to determine the RMS of the harmonic signal are displayed in Fig. 8-10.

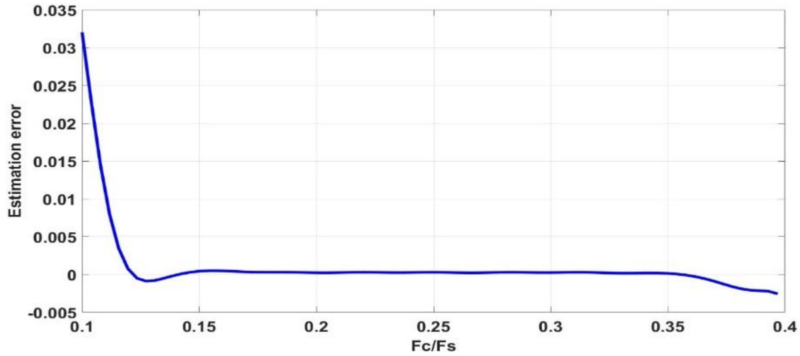

Fig. 8. RMS estimation in the frequency domain with Gauss window at N=16.

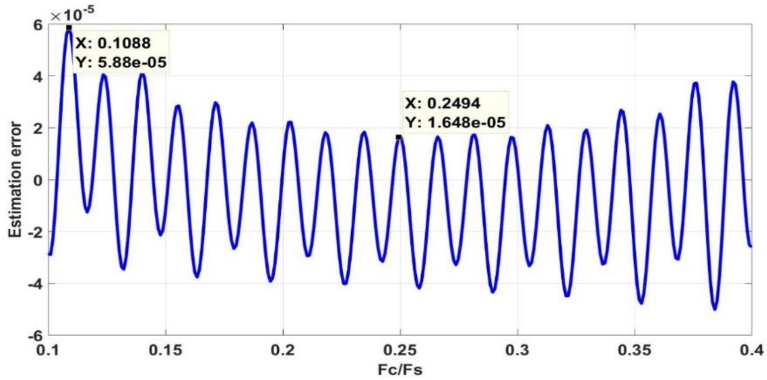

Fig. 9. RMS estimation in the frequency domain with Gauss window at N=32.

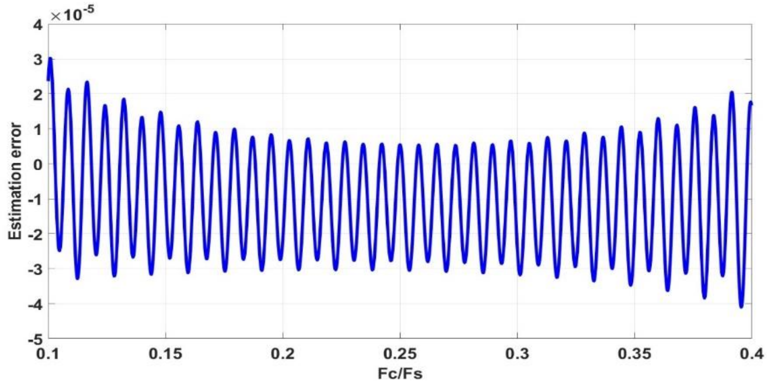

Fig. 10. RMS estimation in the frequency domain with Gauss window at N=64.

The results shown in Fig. 8 to 10 demonstrate that the type of domain has a significant impact on the evaluation error rate, and that the sample size also affects the evaluation results. The graphs show that the maximum evaluation error reached 0.03 at a sample size of 16, and 0.000058 at a sample size of 32, and decreased further when the number of samples increased to 64, where the maximum error reached 0.00003 in the frequency domain. Table 1 shows an important comparison of the results of the three algorithms used in this article.

Table 1. Maximum RMS errors

Domain	The maximum RMS estimation error for varying sample sizes		
	16	32	64
Without windowing, time domain	0.022	0.012	0.006
Windowing function in the time domain	0.014	0.00004	0.00002
With a windowing function, frequency domain	0.03	0.000058	0.00003

6. CONCLUSION

The application of the three algorithms and approaches presented in this article demonstrates the importance of choosing the type of domain (time-frequency) and sample size according to the applications required in the labor market. According to Table 1, it was proven that it is necessary to use the frequency domain for medium and large samples (32 and larger), while the results proved that it is preferable to use the time domain for small samples.

As a reference point, measurements made in the time domain without windowing are shown in Fig. 2-3.

The results shown in Fig. 5 to 7, obtained from the second algorithm in the time domain using a Gaussian window, show a clear improvement in the accuracy of the results for evaluating the error when calculating the RMS. As a conclusion, the improvements range from 30 to 300 times compared to the first algorithm, which was applied without a time window. Fig. 8-10 depict measurements in the frequency domain, also employing a Gaussian window. These figures collectively underscore the effectiveness of the algorithms in accurately measuring RMS values across different methodologies and conditions.

As explained previously, most studies have a significant drawback and challenge: measurements become inaccurate due to the influence of harmonic distortions in the signal. Simulations of the algorithms proposed in this paper have shown that using a Gaussian window overcomes these problems and challenges present in conventional techniques, as the RMS evaluation error is significantly reduced under noise conditions and the SNR is equal to 30 dB.

In the simulation, the best results were obtained with the lowest RMS error of 0.0000054 when the simulation parameters were set to Fc/Fs=0.25 and sample size N=64. The Gaussian window helped in reducing the spectral leakage, which improved the results. To conclude the various algorithms discussed above and the results on RMS measurement, it can be said that all the approaches proposed in this article help solve the challenges currently facing telecommunications research. We recommend the use of AI in future research as a step towards improving the accuracy of RMS assessment.

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