Bitlis Eren Üniversitesi Fen Bilimleri Dergisi
BİTLİS EREN UNIVERSITY JOURNAL OF SCIENCE
ISSN: 2147-3129/e-ISSN: 2147-3188
VOLUME: 13 NO: 4 PAGE: 923-938 YEAR: 2024
DOI: 10.17798/bitlisfen.1471912

A Parameter-Oriented FFT Signal Processing App

Sıtkı AKKAYA[1*],
[1]*Department of Electrical and Electronics Engineering of Faculty of Engineering and Natural Sciences, Sivas University of Science and Technology, Sivas, Turkey*
(ORCID: 0000-0002-3257-7838)

Keywords: Power Quality, FFT, main frequency, sampling frequency, measurement window, visible thinking.

Abstract
In power systems, noise, harmonics, and interharmonics arise in electrical signals due to varying sources and loads, affecting signal purity. Continuous monitoring and accurate analysis of electrical signals are mandatory. The Fast Fourier Transform (FFT) continuously analyzes electrical signals using sliding windows per the IEC-61000-4-7 standard. Parameters from this analysis are compared with threshold values specified in the IEEE-1159 standard. However, variable conditions and factors like sampling frequency, measurement window, main frequency, additional component frequencies, and Signal-to-Noise Ratio (SNR) cause measurement errors. These challenges complicate accurate measurement, leading to errors in preventive measures and control procedures. Understanding the effects of these parameters and improving methods is crucial. The Visible Thinking pedagogical framework is effective in this achievement. This study highlights the importance of parameter selection for FFT and investigates FFT responses to different parameters with synthetical and experimental signal examples. It also presents measurement errors due to signal changes, and a basic interface design shows these errors. Small changes, like a 1/2000 shift in sampling frequency, a 0.5 Hz shift in fundamental frequency, or a 1/1000 difference in the measurement window, cause significant errors. These findings underscore the need for careful parameter selection for accurate computation and signal monitoring, showing the need for FFT method improvements to adapt to changing conditions.

1. Introduction

Within the power systems domain, strict adherence to 50 Hz frequency and 220 V_{rms} standards determined in Turkey is paramount, as the main frequency and amplitude serve as fundamental determinants [1]-[4]. Nevertheless, these critical parameters are susceptible to fluctuations attributed to diverse system components [5]-[8], encompassing nonlinear loads, illumination systems, electrical motors, arc furnaces, and welding operations [9]-[12]. Substantial scholarly inquiry has meticulously scrutinized the complexities inherent in this phenomenon, conducting rigorous analyses and taxonomies [5]–[13]. Standards such as IEEE 1159 and 1459 are dedicated to elucidating power quality parameters and facilitating the revealing evaluation of the measurements in succession. Moreover, detailed guidelines delineating the testing and assessment of disturbances within power systems are expounded in the standards, and an analysis window for power systems is prescribed as 0.2 seconds [1]–[4]. Incorporating disturbance components into the primary signal poses inherent risks and may introduce measurement errors, impacting systems and individuals. These erroneous measurements rather exacerbate the complexity of the issue, impeding the precise determination of values pertaining to components that deserve to be eliminated.

The periodic surveillance and power systems signals analysis are indispensable endeavors. The efficacy of robust adjustment mechanisms, by compensation of filtering, hinges upon the compatibility between signal parameters and the chosen analytical approach.

[*]Corresponding author: sakkaya@sivas.edu.tr
Received: 23.04.2024, Accepted: 23.12.2024

According to the article in [14], the Visible Thinking pedagogical framework is effective in achieving a good complement to traditional lecture–tutorial systems. Moreover, the other study on programming, which is a difficult area to understand due to its notional, proved the positive effect on visible thinking [15]. Indeed, there are limited similar studies for FFT and harmonics for electrical systems directly. For example, a mobile application to teach simple harmonic motions to high school students was made in [16]. A study in [17], presented the VisualHarmony program to learn the harmony effects in musical components by using harmonic analysis. A study in [18], shows that Mobile apps can be used experimentally for physics education. In this study, the ready-made programs are utilized to implement the experiments. In another study, an application of Fourier Theory for optics was implemented for engineering mathematics education [14]. The positive effect of visible thinking is shown in the article. An education tool for signals and systems achieved in MATLAB proposed different transform methods roughly and with some exercises [19]. Different smartphone applications like the Signal Generator, the Function Generator as a tone generator, and the Oscilloscope, the FFTWave as a sound oscilloscope, were performed for teaching the Fourier Series (F.S.) in [20] without any additional programming. It was revealed that the learning rate of F.S. was improved with this method based on Visible Thinking, as shown in the article. A basic signal processing app for sounds was performed with MATLAB [21]. An educational software interface for power electronic applications carried out in [22] provided amplitude monitoring and FFT analysis coarsely. A Fourier Series app based on Android for undergraduate education was performed in [23]. A software based on ISE (Integrated Software Environment) was prepared for harmonics monitoring for FPGA applications in [24]. Another MATLAB app for harmonics was made in [25], and it gave the harmonics results of THD (Total Harmonics Distortion).

As understood from the literature, all solve different problems, and only some approach FFT or harmonics and interharmonics of electrical systems roughly. Consequently, the present study tries to conduct a comprehensive comparative evaluation of parameters with different specifications. In this study, a MATLAB-based software is proposed that enables the generation of harmonic or interharmonic electrical signals, comparative samples with a predefined interface and detailed FFT analysis with different parameters such as sampling frequency (Hz), length (bit), frequency (Hz), main amplitude (V), inserted component frequency, inserted component amplitude (V), SNR level (dB) according to user definition. Moreover, subinterfaces of predetermined comparative parameters based on synthetic and experimental signals are conducted to make the effects of the FFT parameters easy for users to understand.

This manuscript is organized by the following. Section two provides the methodology, including the power signal model and the signal processing model of FFT. The third section details the proposed app that originated on FFT parameters. Time and frequency domain responses obtained from the app are indicated in the next section. The results and effects of the different parameters of FFT are also discussed in this section. A summary of the study, contributions, and future studies are presented in the conclusion.

2. Material and Method

The main amplitude and frequency have crucial roles in power systems engineering, and they are widely acknowledged for their significance. Optimal operational performance within these systems is contingent upon the fidelity of the transmitted signal to a pure sinusoidal waveform characterized by the fundamental frequency. Nonetheless, odd-order harmonics, particularly those within the initial three orders specified by the IEC 61000-4-7 standard, can potentially disrupt these fundamental parameters. Such harmonics or interharmonics may manifest with varying amplitudes, thereby introducing an array of noise manifestations.

2.1. Signal Model

Eq. (1) presents a comprehensive representation of a signal with inserted components. Within this mathematical formulation, the amplitude of the main component is explicitly denoted as $\alpha_{main} = 1$ while the ensuing coefficients $\alpha_{inserted}$ delineate the amplitude of the corresponding inserted harmonic / interharmonic component. The frequencies of the components are also called with similar indices. The term $noise_{SNR}(t)$ signifies the Additive White Gaussian Noise (AWGN) integrated within the signal framework.

$$x(t) = \alpha_{main}\sin(2\pi f_{main}t) + \alpha_{inserted}\sin(2\pi f_{inserted}t) + noise_{SNR}(t) \quad \textbf{(1)}$$

2.2. Signal Processing with FFT

Eq. (2) presents FFT for x called by y with length N:

$$y(k) = \sum_{j=1}^{N} x(j) W_N^{(j-1)(k-1)}, W_N = e^{(-2\pi i)/n} \quad \textbf{(2)}$$

All transformations with different parameters will be done with FFT methods in this study and will not be defined in detail [14]. An input signal as x(t) modeled by Eq. (1) and FFT of it are available in Figure 1. a. and b. consecutively.

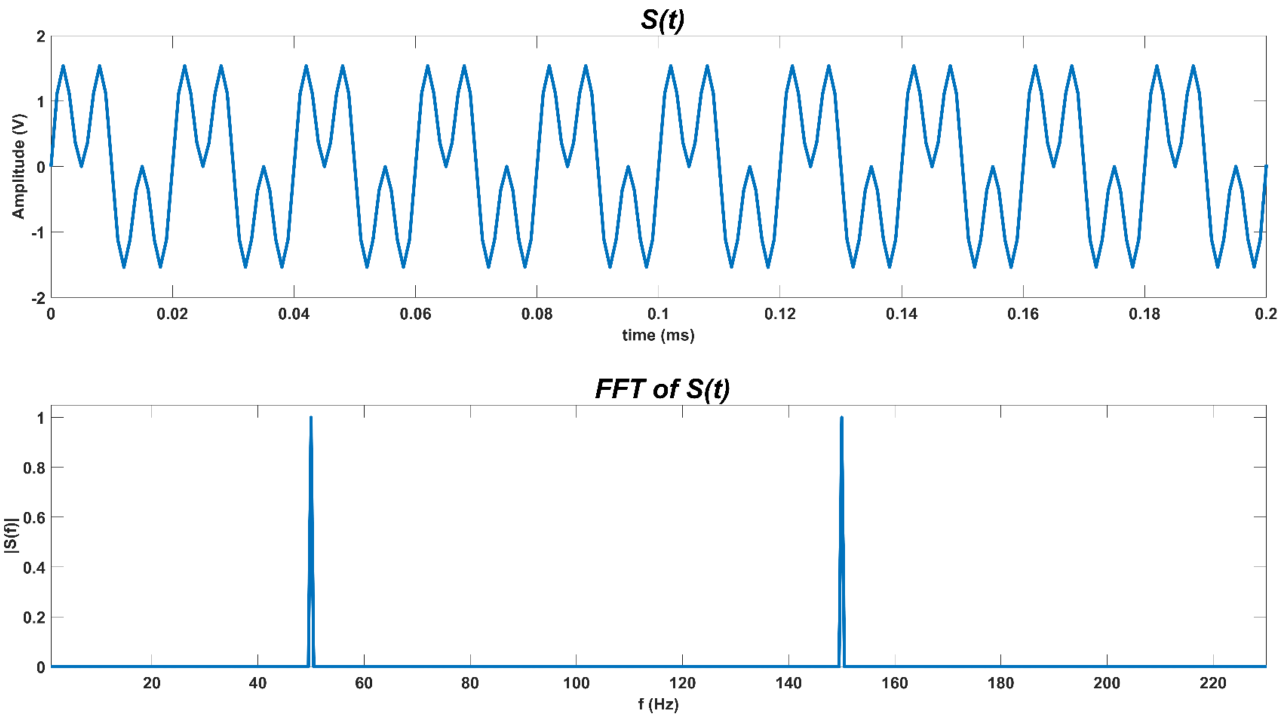

Figure 1. Input Signal and FFT of It

3. Proposed App for Parameter-Oriented FFT

In this study, a MATLAB-based software is proposed that enables the generation of harmonic or interharmonic electrical signals, comparative samples with a predefined interface and detailed FFT analysis with different parameters such as sampling frequency (Hz), length (bit), frequency (Hz), main amplitude (V), inserted component frequency, inserted component amplitude (V), SNR level (dB) according to user definition.

This study proposed an app with three main subprograms, as revealed in Figure 2. The first is a user-defined input interface that allows the user to input phase and time variability. The second provides comparative predefined synthetic signals based on different parameters like sampling frequency, signal length, frequencies of main and inserted components, and SNR level. The last one shows similar signals based on the experimental dataset.

The program is set based on the default parameters available in Table 1. Moreover, the resolution of the FFT and window also important for an accurate measurement are given in Table 1. All parameters are explained why these values are selected as default.

- For this table, the sampling frequency of the signal is selected as $f_s = 1000$ Hz, which provides the 10^{-3}sec according to most basic studies for simplicity.
- The length of the signal is gotten as L=*1500* default. However, it is arranged to different values and performed according to the standard of IEC 61000-4-30 in the simulation studies.
- Window and the resolution effects of the parameters can be obtained from the parameters above. So, they are also performed according to the related values consisting of standard values as $win = 0.2\ sec$ and $res = 5\ Hz$.
- The frequencies of the components f_0 and $f_{inserted}$ are selected with the most common values as 50 and 150 Hz. These are performed for the most common frequency ranges.
- SNR can be encountered between 0 to infinity, so it is arranged as inf, and it can be arranged between 0 to inf.

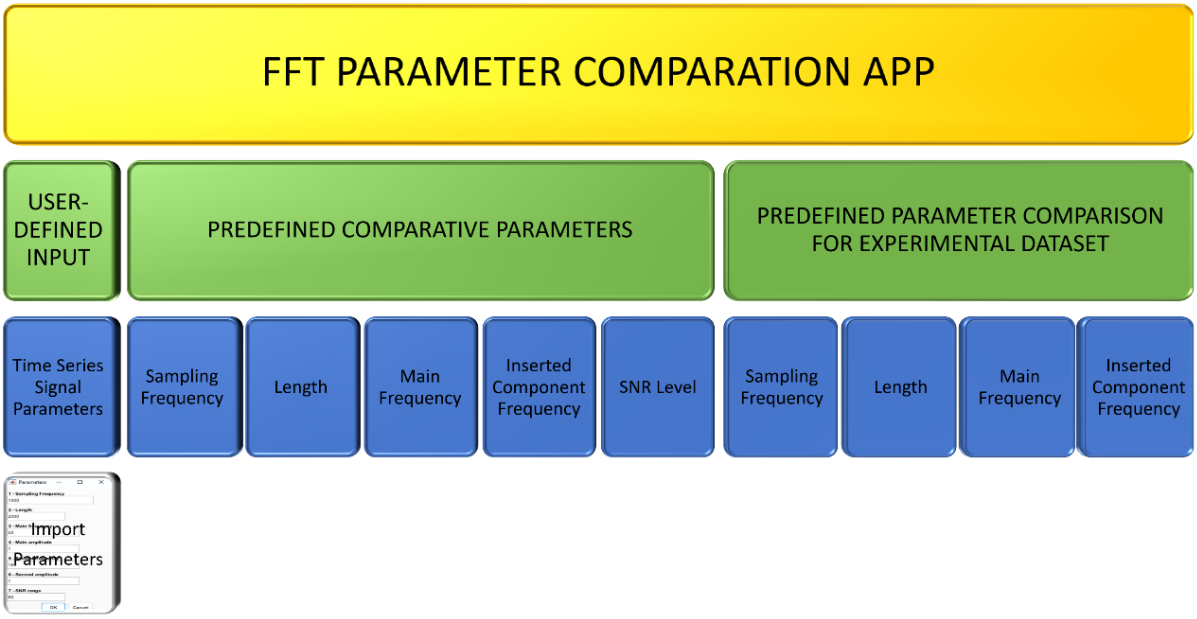

Figure 2. Block Structure of the App

Table 1. Default Parameters of the systems

Default Parameters of the systems	
Sampling Frequency (Hz)	$f_s = 1000$
Sampling period (sec)	$T = 1/f_s$
Length of signal (bit)	$L = 1500$
Window (sec)	$win = L * T$
Resolution (Hz)	$res = f_s/L$
Main Frequency (Hz)	$f_0 = 50$
Inserted Component Frequency (Hz)	$f_{inserted} = 150$
SNR Level (dB)	∞

3.1. Input Option

The program presented allows for user login and predefined operations. The interface in Figure 3 offers the options of selecting User-Defined Input, Predefined Comparative Parameters or Predefined Comparative Experimental Parameters by selecting in order of 1, 2 or 3.

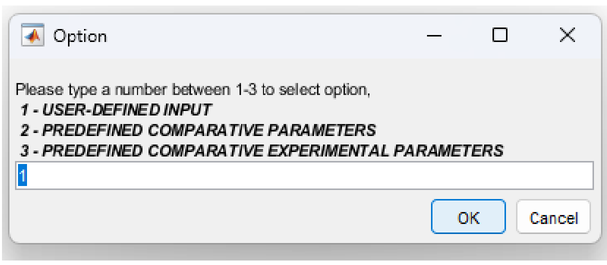

Figure 3. Input Selection Sub-Interface

3.1.1. User-Defined Input

The user-defined input interface that appears in Figure 4 makes an easier arrangement of parameters like sampling frequency, length, main frequency, main amplitude, inserted component frequency, inserted component frequency, and SNR level, successively as seen in the figure.

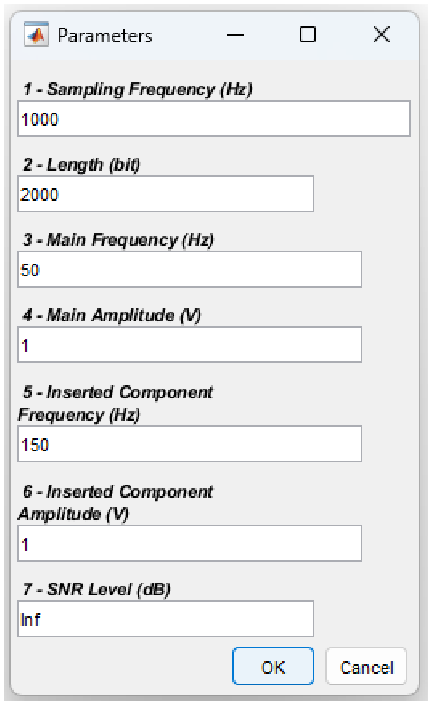

Figure 4. User-Defined Input Sub-Interface

3.1.2. Predefined - Comparative Parameters

The Predefined Parameter interface shown in Figure 5, is usable to see comparative results that align with the selected parameter while the others are default parameters. The details of the results will be observed in the next section.

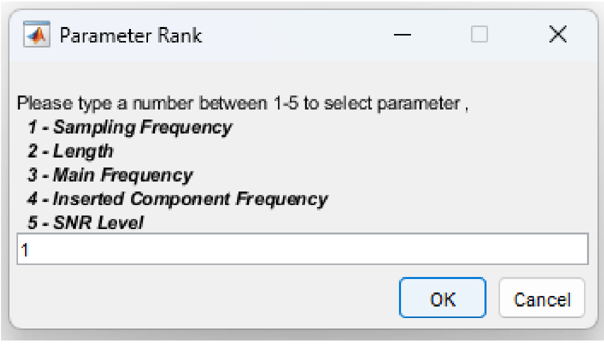

Figure 5. Parameter Selection Sub-Interface for Predefined Comparative Parameters

3.1.3. Predefined - Comparative Experimental Parameters

The Predefined Experimental Parameter interface shown in Figure 6, is usable to see comparative results that align with the selected parameter while the others are default parameters. The details of the results will be observed in the next section.

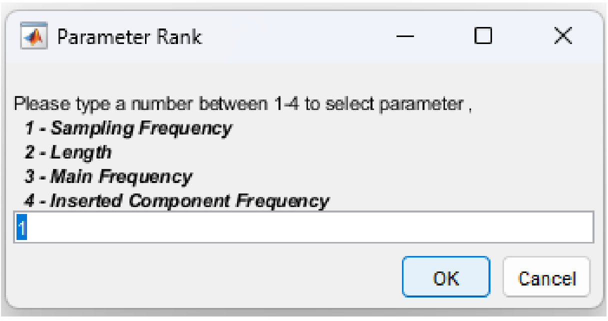

Figure 6. Parameter Selection Sub-Interface for Predefined Comparative Experimental Parameters

4. Results And Discussion

In this study, an application for FFT is based on the parameters. The computation was performed with MATLAB 2024a on a computer with Intel(R) Core(TM) i7-10700 CPU @ 2.90GHz 2.90 GHz, 64-bit processor, 32 GB RAM. The elapsed time is 0.071373 seconds, which is less than a window length of 0.2 seconds. That means it leads to only 0.071373 seconds delaying the process of a window, and it can be tolerated until the other window acquisition. In this section, the comparative results for predefined values are obtained for the “5” different parameters with figures and tables in the case of synthetical and experimental datasets as follows.

4.1. Synthetical Results

4.1.1. Sampling Frequency

Figure 7 demonstrates the effects of the different sampling frequencies. It is clear that the appropriate sampling frequency selection is important for accurate measurement in the frequency spectrum. The results of this comparison are given in Table 2. Both components are measured with 0% error in the case of $f_s = 1000$, while important errors occur in terms of frequency and amplitude under the other cases. These errors depend on frequency resolution.

Table 2. Results for different sampling frequencies

	Main Component			***Inserted Component***		
Sampling Frequency, f_s	1000	2000	2994	1000	2000	2994
Frequency Resolution (Hz)	0.6667	1.3333	1.996	0.6667	1.3333	1.996
Nominal Amplitude (V_{pu})	1	1	1	1	1	1
Nominal Frequency (Hz)	50	50	50	150	150	150
Measured Amplitude (V_{pu})	1	0.647	0.996	1	0.637	0.961
Error (%)	**0**	**-35.3**	**-0.4**	**0**	**-36.3**	**-3.9**
Measured Frequency (Hz)	50	49.33	49.9	150	150.67	149.7
Error (%)	**0**	**-1.34**	**-0.2**	**0**	**+0.45**	**-0.2**

4.1.2. Length

Figure 8 demonstrates the effects of the different signal lengths. The appropriate length selection is important for accurate measurement, as shown in this figure. The results of the comparison are available in Table 3. Both components are measured with 0% error under the case of $L = 1500$ and 200, while important errors occur in terms of frequency and amplitude under the case of $L = 1001$. Because the frequency resolution is 0.999 that leads to a -0.1 % and -0.45% frequency deviation for both components. This result is related directly to the measurement window.

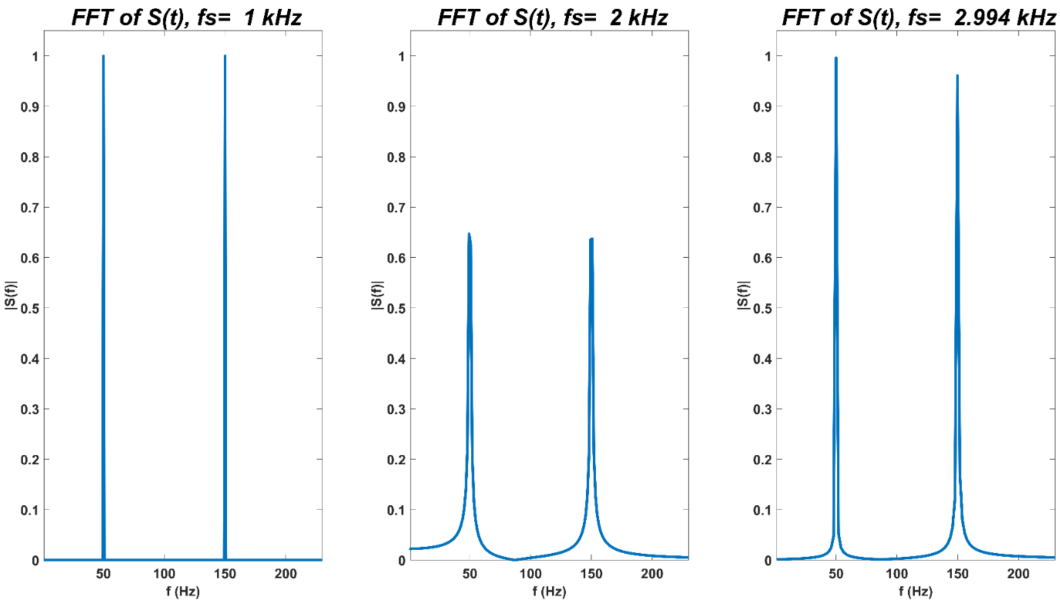

Figure 7. Effects of different sampling frequencies

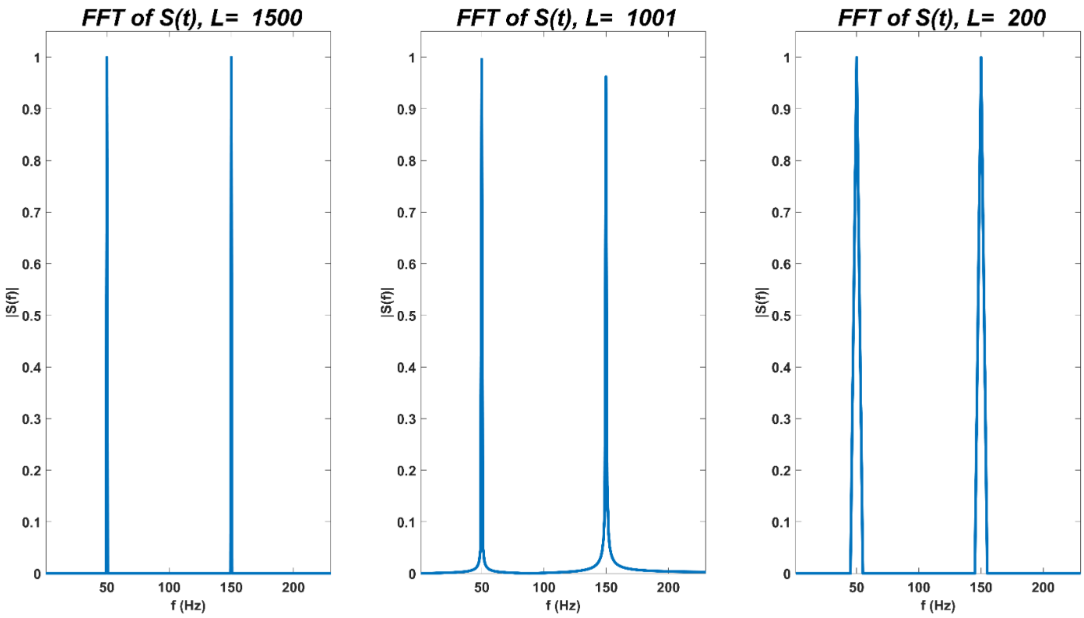

Figure 8. Effects of different signal lengths

Table 3. Results for different signal lengths

	Main Component			***Inserted Component***		
Length of Signal, L	1500	1001	200	1500	1001	200
Frequency Resolution (Hz)	0.667	0.999	5	0.6667	0.999	5
Nominal Amplitude (V_{pu})	1	1	1	1	1	1
Nominal Frequency (Hz)	50	50	50	150	150	150
Measured Amplitude (V_{pu})	1	0.996	1	1	0.962	1
Error (%)	**0**	**-0.4**	**0**	**0**	**-3.8**	**0**
Measured Frequency (Hz)	50	49.95	50	150	149.85	150
Error (%)	**0**	**-0.1**	**0**	**0**	**-0.45**	**0**

4.1.3. Main Frequency

Figure 9 demonstrates the effects of the main frequency value. An appropriate main frequency value is also important for accurate measurement, as shown in this figure. The results of this effect are presented in Table 4. Both components are measured with 0% error in the case of $f_{main} = 50\ Hz$, while important errors occur in terms of frequency and amplitude under the cases of $f_{main} = 49.5\ Hz$, and 50.5 Hz for the main component. The inserted component is measured accurately in all cases. Because the frequency value of the main component affects itself independently from the other components.

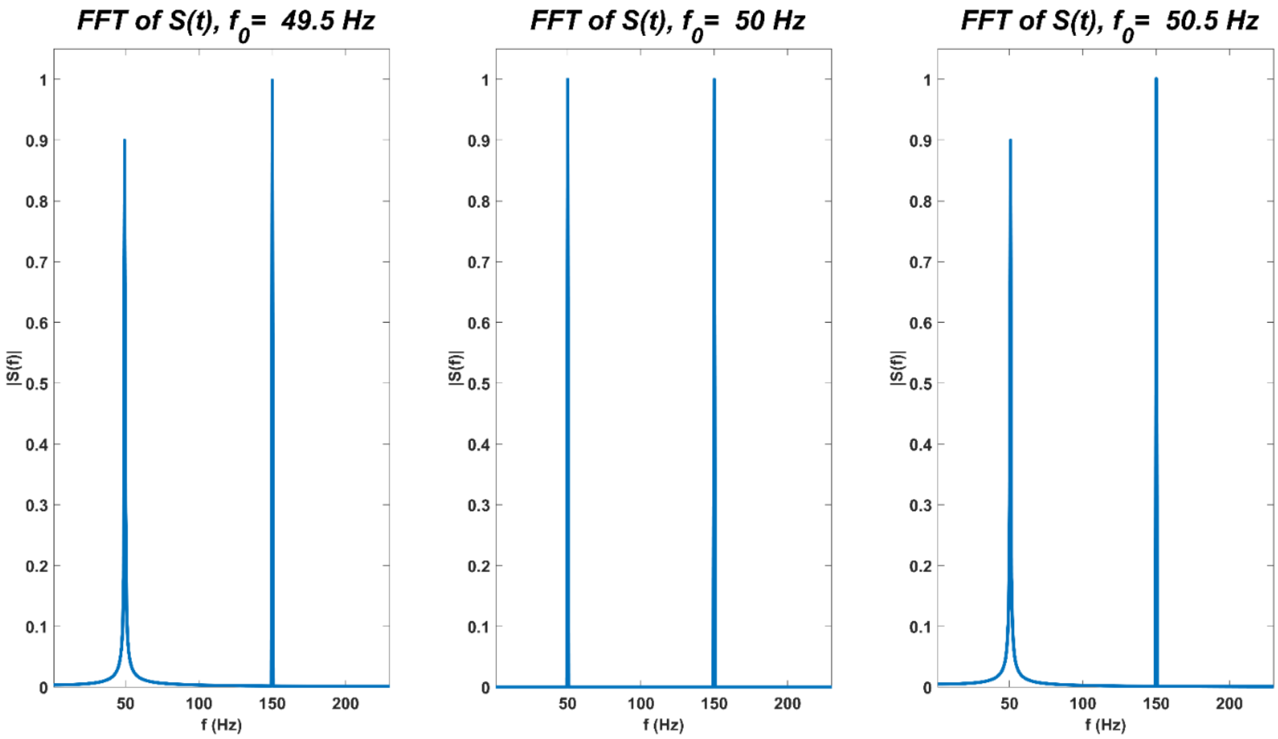

Figure 9. Effects of different main frequencies

Table 4. Results for different main frequencies

	Main Component			***Inserted Component***		
Main Frequency, f_0 (Hz)	49.5	50	50.5	150	150	150
Frequency Resolution (Hz)	0.667	0.667	0.667	0.667	0.667	0.667
Nominal Amplitude (V_{pu})	1	1	1	1	1	1
Nominal Frequency (Hz)	50	50	50	150	150	150
Measured Amplitude (V_{pu})	0.8998	1	0.8998	1	1	1
Error (%)	**-10.02**	**0**	**10.02**	**0**	**0**	**0**
Measured Frequency (Hz)	49.333	50	50.667	150	150	150
Error (%)	**-1.334**	**1**	**1.334**	**0**	**0**	**0**

4.1.4. Inserted Component Frequency

Figure 10 demonstrates the effects of the inserted component frequency value. An appropriate inserted component frequency value is also important for accurate measurement, as shown in this figure. The results of this effect are presented in Table 5. Both components are measured with 0% error in the case of $f_{inserted} = 100\ Hz$, and 150 Hz, while important errors occur in terms of frequency and amplitude under the cases of $f_{inserted} = 149\ Hz$ for just the inserted component. The main component is measured accurately in all cases. Similar to that, in the cases of main frequency, the value of the inserted component frequency only affects itself independently from the other components.

Table 5. Results for different inserted component frequencies

	Main Component			***Inserted Component***		
Inserted Component Frequency, $f_{inserted}$ (Hz)	50	50	50	150	149	100
Frequency Resolution (Hz)	0.667	0.667	0.667	0.667	0.667	0.667
Nominal Amplitude (V_{pu})	1	1	1	1	1	1
Nominal Frequency (Hz)	50	50	50	150	150	150
Measured Amplitude (V_{pu})	1	1	0	1	0.667	1
Error (%)	**0**	**0**	**0**	**0**	**-33.3**	**0**
Measured Frequency (Hz)	50	50	50	150	148.67	150
Error (%)	**0**	**0**	**0**	**0**	**-0.89**	**0**

4.1.5. SNR Level

Figure 11 demonstrates the effects of SNR level for the inserted noise. The noise level is also important for accurate measurement as seen in this figure. The results of this effect are presented in Table 6. Both components are measured with almost errorless under the case of $SNR = 50\ dB$, and $30\ dB$ while important errors occur in terms amplitude in the case of $SNR = 3\ dB$ for both components.

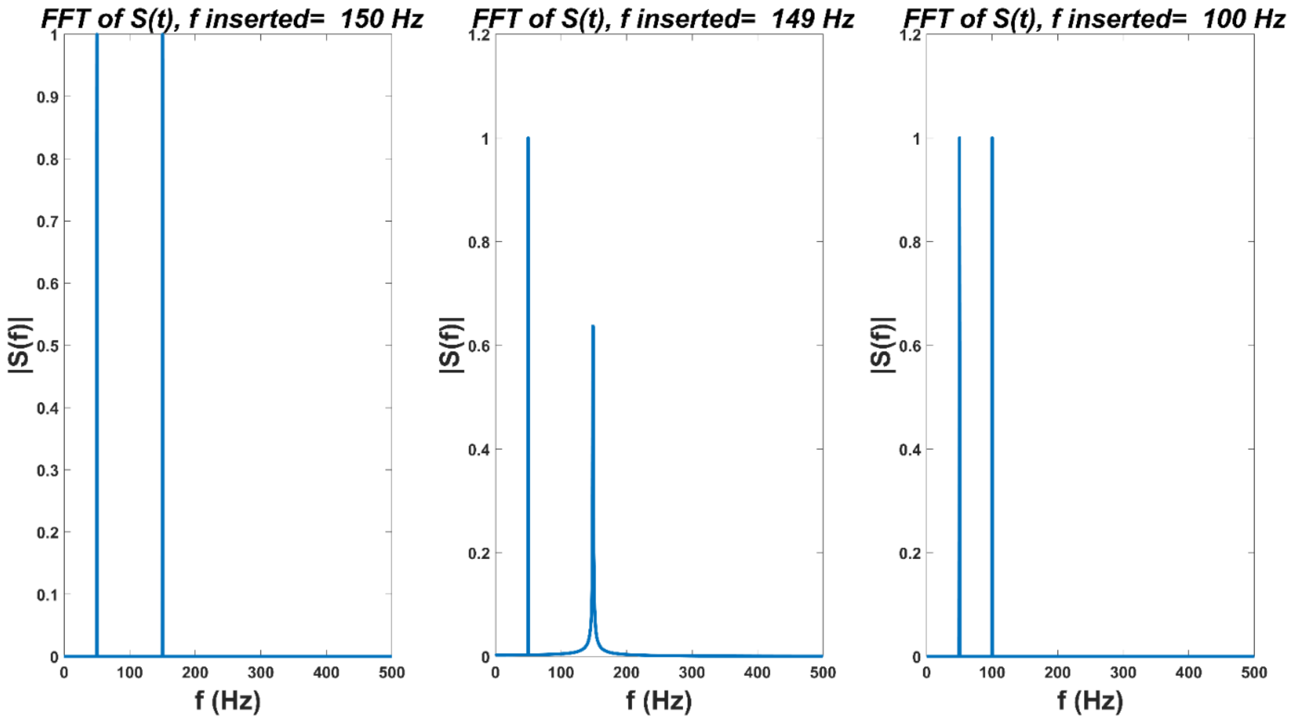

Figure 10. Effects of different inserted component frequencies

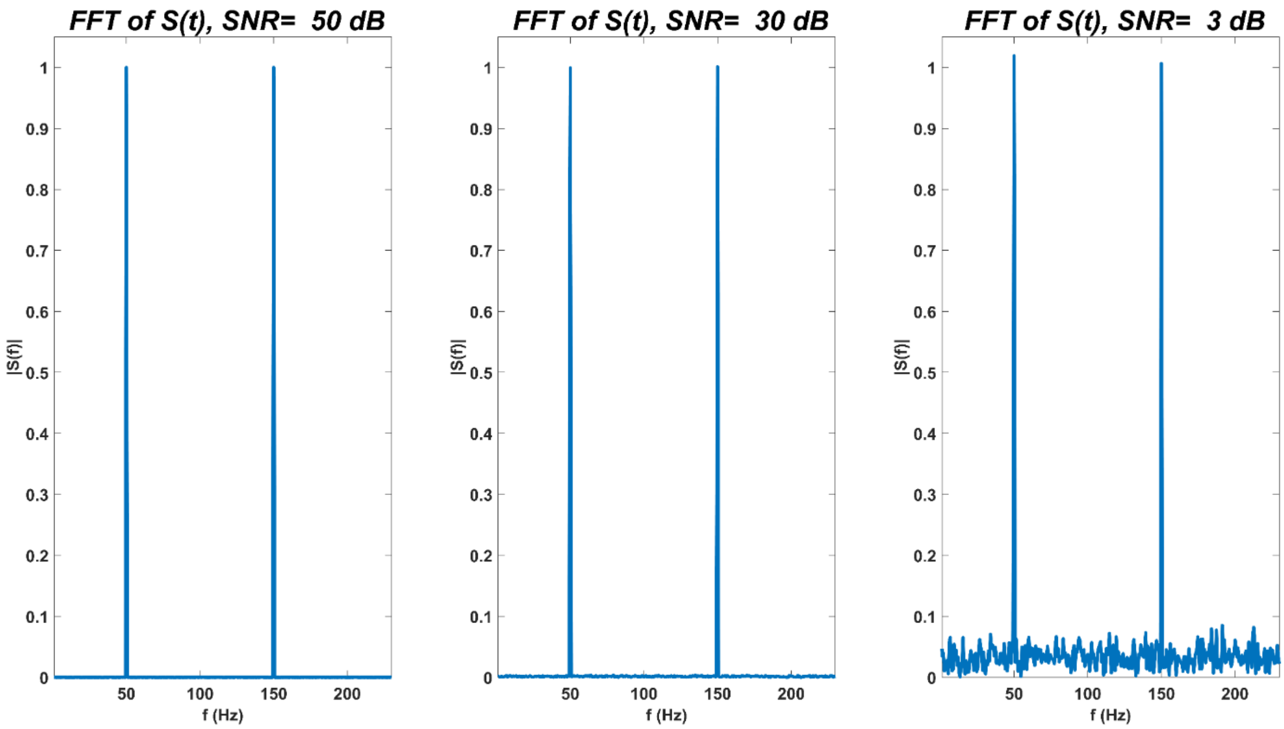

Figure 11. Effects of different SNR levels

Table 6. Results for different SNR levels

	Main Component			Inserted Component		
SNR (dB)	50	30	3	50	30	3
Frequency Resolution (Hz)	0.667	0.667	0.667	0.667	0.667	0.667
Nominal Amplitude (V_{pu})	1	1	1	1	1	1
Nominal Frequency (Hz)	50	50	50	150	150	150
Measured Amplitude (V_{pu})	0.9999	0.9991	0.9857	1.00003	1.0004	0.957
Error (%)	**-0.01**	**-0.093**	**-1.433**	**0.003**	**0.041**	**-4.32**
Measured Frequency (Hz)	50	50	50	150	150	150
Error (%)	**0**	**0**	**0**	**0**	**0**	**0**

4.2. Experimental Results

An experimental dataset is generated by an adjustable signal generator in the laboratory. According to the ability of the generator, all comparisons are carried out except for the SNR level as follows. Default parameters for the experimental dataset are selected based on the properties and IEC 6100-4-7 standard recommendations of window 0.2 secs, as in Table 7.

Table 7. Default parameters of the systems for experimental dataset.

Default parameters of the systems	
Sampling Frequency (Hz)	$f_s = 5000$
Sampling period (sec)	$T = 1/f_s$
Length of signal (bit)	$L = 1000$
Window (sec)	$win = L * T$=*0.2 sec*
Resolution (Hz)	$res = f_s/L$ = *5 Hz*
Main Frequency (Hz)	$f_0 = 50$
Inserted Component Frequency (Hz)	$f_{inserted} = 150$
SNR Level (dB)	*Natural Grid Noise*

4.2.1. Sampling Frequency

Figure 12 demonstrates the effects of the different sampling frequencies for experimental time series data. The appropriate sampling frequency selection is important for accurate measurement in the frequency spectrum. The results of this comparison are given in Table 8. Both components are measured with a low error rate in the cases of $f_s = 1000$ and 5000 Hz, while important errors occur in terms of frequency and amplitude under the case of $f_s = 7150$. These errors depend on frequency resolution. The measured amplitudes of the components are *1.024* and *0.9832* V_{pu} because of the natural grid noise of the signal. This is also true for the other cases of the experimental parameters as follows.

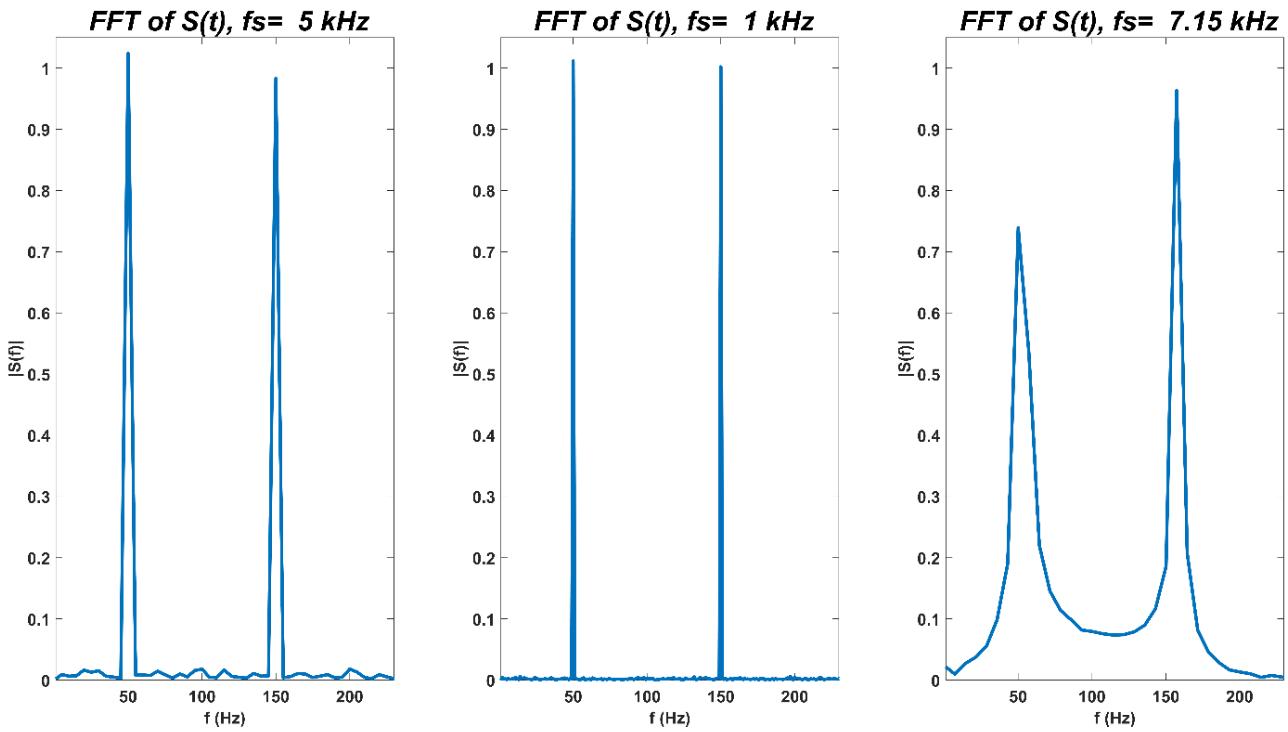

Figure 12. Effects of different sampling frequencies for experimental dataset

Table 8. Results for different sampling frequencies for experimental dataset

	Main Component			Inserted Component		
Sampling Frequency, f_s	5000	1000	7150	5000	1000	7150
Frequency Resolution (Hz)	5	1	7.15	5	1	0.696
Nominal Amplitude (V_{pu})	1	1	1	1	1	1
Nominal Frequency (Hz)	50	50	50	150	150	150
Measured Amplitude (V_{pu})	1.024	1.012	0.739	0.983	1.002	0.9636
Error (%)	**+2.4**	**+1.17**	**-26.1**	**-1.68**	**+0.22**	**-3.64**
Measured Frequency (Hz)	50	50	50.05	150	150	157.3
Error (%)	**0**	**0**	**+0.1**	**0**	**0**	**+3.65**

4.2.2. Length

Figure 13 gives the effects of the different signal lengths for experimental data. The appropriate length selection is important for accurate measurement as shown in this figure. The results of the comparison are available in Table 9. Both components are measured with a low error rate under the case of $L = 1000$ and 15000, while important errors occur in terms of frequency and amplitude under the case of $L = 14371$. Because the frequency resolution is 0.6958 that leads to a 0.202 % frequency deviation for both components. This result is related directly to the measurement window.

Table 9. Results for different signal lengths for the experimental dataset

	Main Component			Inserted Component		
Length of Signal, L	1000	15000	14371	1000	15000	14371
Frequency Resolution (Hz)	5	0.6667	0.696	5	0.667	0.696
Nominal Amplitude (V_{pu})	1	1	1	1	1	1
Nominal Frequency (Hz)	50	50	50	150	150	150
Measured Amplitude (V_{pu})	1.0240	1.005	0.97	0.983	1.0038	0.72
Error (%)	**+2.4**	**+0.5**	**-3**	**-1.68**	**+0.38**	**-28**
Measured Frequency (Hz)	50	50	50.101	150	150	150.303
Error (%)	**0**	**0**	**+0.202**	**0**	**0**	**+0.202**

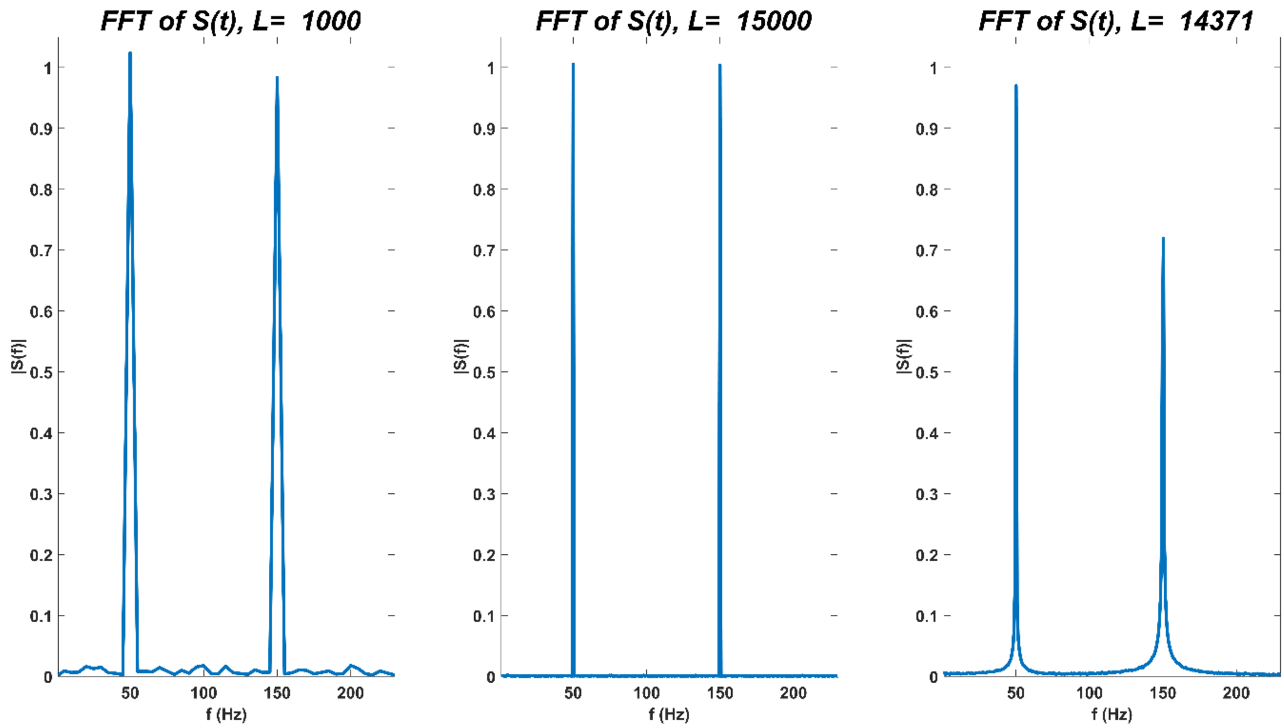

Figure 13. Effects of different main frequencies for experimental dataset

4.2.3. Main Frequency

Figure 14 illustrates the effects of the main frequency value in the case of experimental data. An appropriate main frequency value is also important for accurate measurement, as shown in this figure. The results of this effect are presented in Table 10. Both components are measured with a low error rate in the case of $f_{main} = 50\ Hz$. In contrast, important errors occur in terms of frequency and amplitude under the cases of $f_{main} = 49.5$ and $50.5\ Hz$ for the main component. The inserted component is measured accurately in all cases. Because the frequency value of the main component affects itself independently from the other components.

Table 10. Results for different main frequencies for experimental data

	Main Component			***Inserted Component***		
Main Frequency, f_0 (Hz)	49.5	50	50.5	150	150	150
Frequency Resolution (Hz)	5	5	5	5	5	5
Nominal Amplitude (V_{pu})	1	1	1	1	1	1
Nominal Frequency (Hz)	50	50	50	150	150	150
Measured Amplitude (V_{pu})	1.002	1.0240	0.99	1.005	0.9832	1.007
Error (%)	**+0.2**	**+2.4**	**+1**	**0.5**	**-1.68**	**+0.7**
Measured Frequency (Hz)	50	50	50	150	150	150
Error (%)	**+1.0101**	**1**	**-0.990**	**0**	**0**	**0**

4.2.4. Inserted Component Frequency

Figure 15 reveals the effects of the inserted component frequency value for experimental data. An appropriate inserted component frequency value is also important for accurate measurement, as shown in this figure. The results of this effect are presented in Table 11. Both components are measured with a low error rate in the case of $f_{inserted} = 100\ Hz$, and 150 Hz, while important errors occur in terms of frequency and amplitude under the cases of $f_{inserted} = 149\ Hz$ for just the inserted component. The main component is measured accurately in all cases. Similar to that in the cases of main frequency, the value of the inserted component frequency only affects itself independently from the other components.

Table 11. Results for different inserted component frequencies for experimental data

	Main Component			***Inserted Component***		
Inserted Component Frequency, $f_{inserted}$ (Hz)	50	50	50	150	149	100
Frequency Resolution (Hz)	5	5	5	5	5	5
Nominal Amplitude (V_{pu})	1	1	1	1	1	1
Nominal Frequency (Hz)	50	50	50	150	150	150
Measured Amplitude (V_{pu})	1.024	1.028	1.016	0.983	0.951	1.0021
Error (%)	**+2.4**	**+2.81**	**+1.61**	**-1.68**	**-4.1**	**+0.21**
Measured Frequency (Hz)	50	50	50	150	150	150
Error (%)	**0**	**0**	**0**	**0**	**+1.0067**	**0**

4.3. Comparison of the proposed method

The proposed study on harmonic- / interharmonic-signal generation and analysis with different parameters comprehensively on electrical systems has been compared with 11 different studies in Table 12 is established with It outperforms in this field in terms of parameters like interharmonic-, length effect, frequency deviation effect, and noise effect. Furthermore, all parameters are assured by the proposed method.

All results show that values of the parameters, such as sampling frequency, signal length, amplitudes and frequencies of main and inserted components, and SNR level, are effective for the correct measurement. These are presented for the user predefined and comparatively in this app to understand the effects. If one would like to generate and analyze a user-defined signal with additional components, he/she can use the app's user-defined input interface.

This study offers users different choices, such as training, generating, and analyzing a signal with different interfaces of the proposed app.

The proposed method's limitation is that only one harmonic or interharmonic can be inserted into the fundamental frequency signal at any noise level of AWGN instead of more than one related component.

Table 12. Comparison of proposed and similar studies in the literature

Methods	**Fields**	**FFT**	**Harmonics**	**Interharmonics**	**Length Effect**	**Frequency Deviation Effect**	**Noise Effect**	**Generation**	**Analysis**	**Examples**	**Programming Language**
[14]	Optics	✓ Fourier Theory	✓	✗	✗	✗	✗	✓	✓	✓	Java
[16]	Physics	✗	✓	✗	✗	✗	✗	✗	✗	✗	Android
[17]	Music	✗	✓	✗	✗	✗	✗	✗	✓	✗	Java
[18]	Physics	✗	✗	✗	✗	✗	✗	✓	✓	✗	Android
[19]	Signals and Systems	✓	✓	✗	✗	✗	✗	✓	✓	✓	MATLAB
[20]	Sounds	✓ Fourier Series	✓	✗	✗	✗	✗	✓	✓	✗	✗
[21]	Sounds	✓	✗		✗	✗	✗	✗	✓	✗	MATLAB
[22]	Power Electronics	✓	✓	✗	✗	✗	✗	✓	✓	✗	Labview
[23]	Electrical and Electronics Engineering	✓ Fourier Series	✓	✗	✗	✗	✗	✓	✓	✗	Android
[24]	Electrical Systems	✓	✓	✗	✗	✗	✗	✓	✓	✗	ISE
[25]	Electrical Systems	✓ Fourier Series	✓	✗	✗	✗	✗	✗	✓	✗	MATLAB
Proposed Method	Electrical Systems	✓	✓	✓	✓	✓	✓	✓	✓	✓	MATLAB

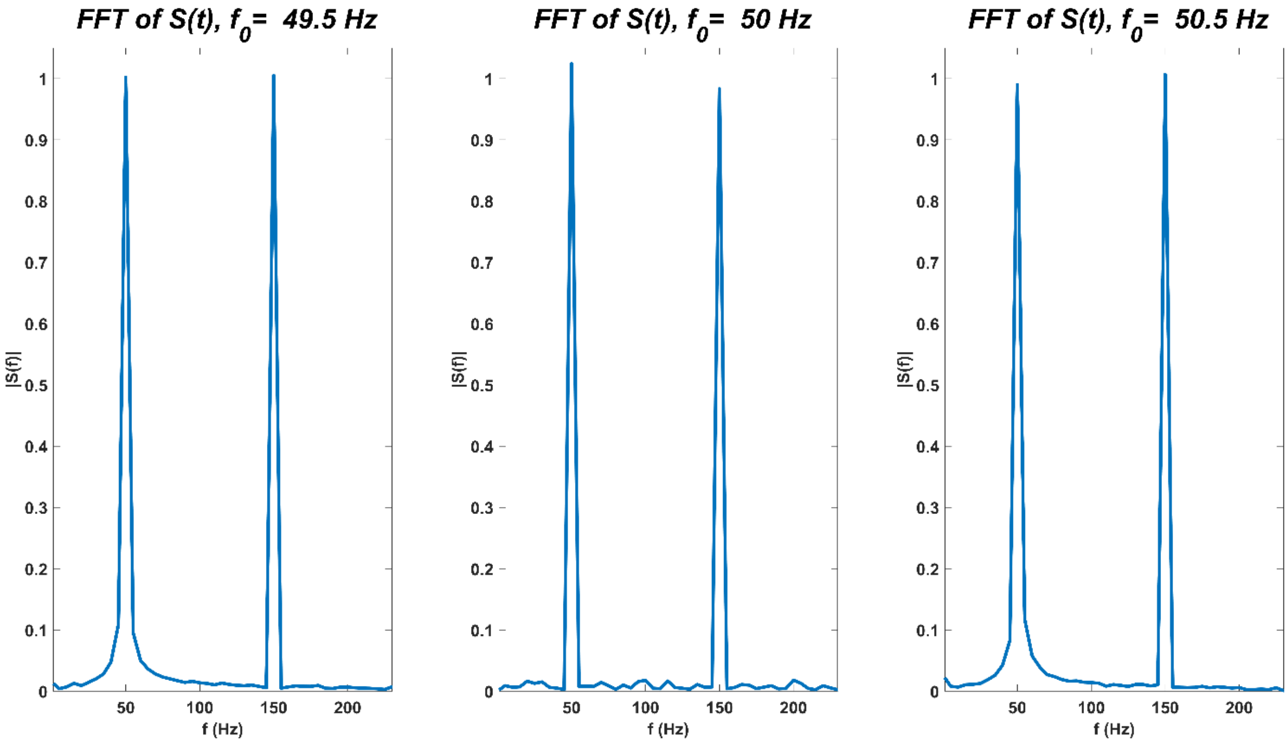

Figure 14. Effects of different lengths for experimental dataset

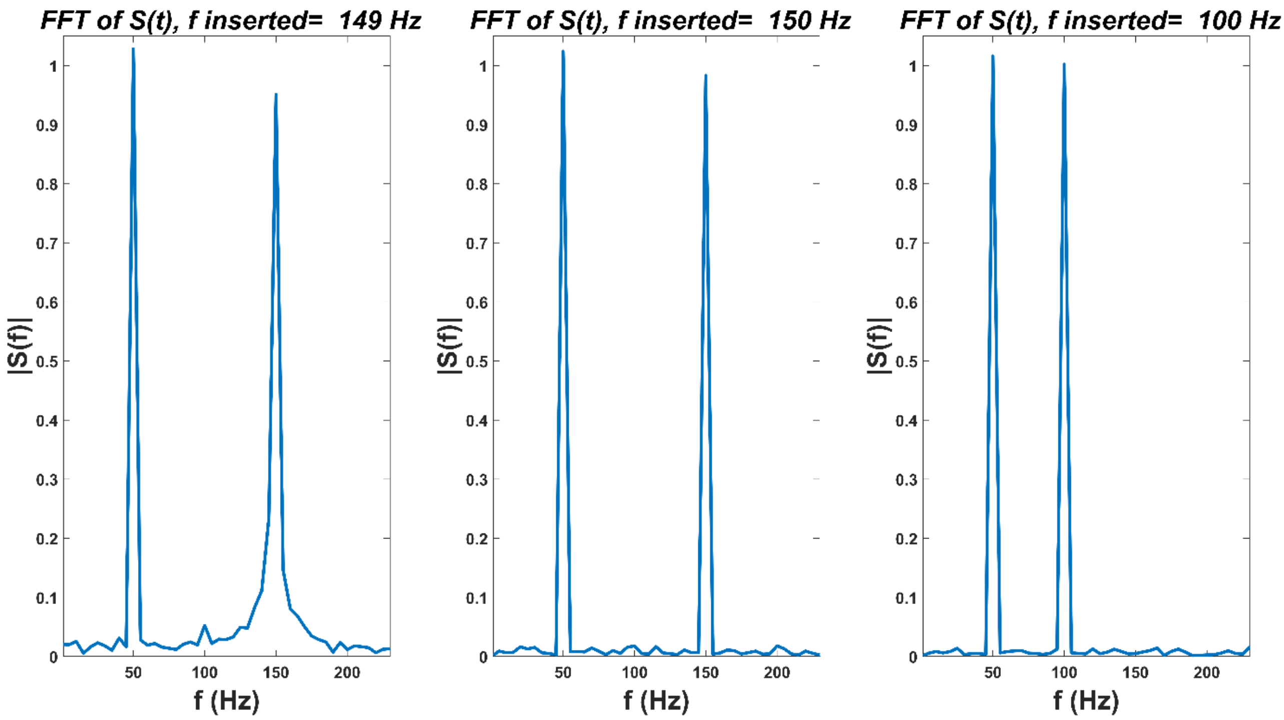

Figure 15. Effects of different inserted component frequencies for experimental dataset

5. Conclusion and Suggestions

The conclusion section should be stand-alone. The aim of the study and its significant results should be given briefly in a concrete way. In addition, suggestions and opinions that are requested to be conveyed to the readers regarding the results of the study can be stated.

In summary, this paper presents an enhanced comparative investigation concerning the FFT based on related parameters, encompassing the analysis of power signals containing disturbance components such as harmonics / interharmonics, and noise with not only synthetical signals but also experimental signals. The findings of the FFT analysis, involving parameters including α_{main}, $\alpha_{inserted}$, f_{main}, $f_{inserted}$, f_s, L, and SNR of noise, reveal that alterations in the mentioned specific parameters exert a localized impact solely on individual component values. In contrast, variations in the remaining FFT parameters affect the entirety of the measured values across all processed components. Moreover, it was found that small changes in the sampling frequency of 1/2000, the fundamental frequency of 0.5 Hz, or the measurement window of 1/1000 caused very large errors. Furthermore, the paper introduces a rudimentary application facilitating the comparison of these parameters and examining resultant outcomes. This research contributes to advancing the understanding of disturbance components and noise within signal-processing contexts. Additionally, it highlights important parameters that affect the analysis and effectiveness of FFT-based study across different parameter circumstances. Furthermore, users can easily understand the effects of the FFT parameters employing subinterfaces of predetermined comparative parameters based on synthetic and experimental data. This study offers different choices to users, such as training, generating, and analyzing a signal with different interfaces of the proposed app. Although this application has been designed for power system signals, it also applies to biomedical, audio, and other electrical signal studies.

Acknowledgment

The author would like to thank the Sivas University of Science and Technology, Department of Electrical Electronics Engineering, Smart Grids Laboratory.

Statement of Research and Publication Ethics

The study complies with research and publication ethics.

References

[1] "General guide on harmonics and interharmonics measurements and measuring instruments for power supply networks and attached devices used for the measurements", *IEC Standard 61000-4-7,* 2008.

[2] "Testing and measurement techniques - Power quality measurement methods", *IEC Standard 61000-4-30,* 2003.

[3] "IEEE Standard Definitions for the Measurement of Electric Power Quantities Under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions," *IEEE Std 1459-2010*, pp.1-50, 19 March 2010, doi: 10.1109/IEEESTD.2010.5439063

[4] "IEEE Recommended Practice for Monitoring Electric Power Quality, "*IEEE Std 1159-2019*, pp.1-98, 13 Aug. 2019, doi: 10.1109/IEEESTD.2019.8796486

[5] S. Akkaya and Ö. Salor, "Flicker Detection Algorithm Based on the Whole Voltage Frequency Spectrum for New Generation Lamps – Enhanced VPD Flickermeter Model and Flicker Curve," *Electric Power Components and Systems*, vol. 0, no. 0, pp. 1–15, 2022, doi: 10.1080/15325008.2021.2011487.

[6] S. Akkaya and Ö. Salor, "New flickermeter sensitive to high-frequency interharmonics and robust to fundamental frequency deviations of the power system," *IET Science, Measurement and Technology*, vol. 13, no. 6, 2019, doi: 10.1049/iet-smt.2018.5338.

[7] S. Akkaya and Ö. Salor, "A new flicker detection method for new generation lamps both robust to fundamental frequency deviation and based on the whole voltage frequency spectrum," *Electronics (Switzerland)*, vol. 7, no. 6, 2018, doi: 10.3390/electronics7060099.

[8] S. Akkaya and Ö. S. Durna, "Enhanced spectral decomposition method for light flicker evaluation of incandescent lamps caused by electric arc furnaces," *Journal of the Faculty of Engineering and Architecture of Gazi University*, vol. 2018, no. 18–2, pp. 987–1005, 2018, doi: 10.17341/gazimmfd.460497.

[9] S. Akkaya, “A Review of the Experimental Studies on Analysis of Power Quality Disturbances,” in *Pioneer and Contemporary Studies in Engineering*, 2023, pp. 453–477.

[10] S. Akkaya, “An Overview of the Empirical Investigations into the Classification of Power Quality Disturbances,” in *Pioneer and Contemporary Studies in Engineering*, 2023, pp. 409–430.

[11] S. Akkaya, “A Conspectus of PQD Analysis,” in *ICAENS*, 2023, pp. 325–329. [Online]. Available: https://as-proceeding.com/index.php/icaens/article/view/1015/950 . [Accessed: Dec. 11, 2004].

[12] S. Akkaya, “Empirical Investigations: Power Quality Disturbance Classification,” in *ICAENS*, 2023, pp. 320–324. [Online]. Available: https://as-proceeding.com/index.php/icaens/article/view/1014/949 . [Accessed: Dec. 11, 2004].

[13] S. Akkaya, E. Yüksek, and H. M. Akgün, “A New Comparative Approach Based on Features of Subcomponents and Machine Learning Algorithms to Detect and Classify Power Quality Disturbances,” *Electric Power Components and Systems*, 2023, doi: 10.1080/15325008.2023.2260375.

[14] K. H. Cheong and J. M. Koh, “Integrated virtual laboratory in engineering mathematics education: Fourier theory,” *IEEE Access*, vol. 6, pp. 58231–58243, 2018, doi: 10.1109/ACCESS.2018.2873815.

[15] Y. Y. Zhuang, Y. H. Lin, M. Liyanawatta, A. H. Saputro, Y. D. Utami, and J. H. Wang, “An interactive programming learning environment supporting paper computing and immediate evaluation for making thinking visible and traceable,” *Interactive Learning Environments*, 2023, doi: 10.1080/10494820.2023.2212709.

[16] B. Pambayun, J. V. D. Wirjawan, H. Herwinarso, A. Wijaya, B. Untung, and E. Pratidhina, “Designing Mobile Learning App to Help High School Students to Learn Simple Harmonic Motion,” *International Journal on Social and Education Sciences*, vol. 1, no. 1, 2019.

[17] D. Malandrino, D. Pirozzi, and R. Zaccagnino, “Learning the harmonic analysis: is visualization an effective approach?,” *Multimed Tools Appl*, vol. 78, no. 23, pp. 32967–32998, Dec. 2019, doi: 10.1007/s11042-019-07879-5.

[18] D. Buongiorno and M. Michelini, “Experimental use of mobile apps in physics education,” *AAPP Atti della Accademia Peloritana dei Pericolanti, Classe di Scienze Fisiche, Matematiche e Naturali*, vol. 99, 2021, doi: 10.1478/AAPP.99S1A22.

[19] F. Vatansever and N. A. Yalcin, “e-Signals&Systems: A web-based educational tool for signals and systems,” *Computer Applications in Engineering Education*, vol. 25, no. 4, pp. 625–641, Jul. 2017, doi: 10.1002/cae.21826.

[20] C. S. Wang, “Teaching Fourier series with tone experiments based on smartphone applications,” *Computer Applications in Engineering Education*, vol. 31, no. 5, pp. 1358–1371, Sep. 2023, doi: 10.1002/cae.22644.

[21] P. C. P. S. Andreas Spanias, “A New Signal Processing Course for Digital Culture,” in *Frontiers in Education 2015 : launching a new vision in engineering education*, IEEE, 2015.

[22] A. Marquez, J. I. Leon, L. G. Franquelo, and S. Vazquez, “Educational Hardware/Software Interface for Power Electronic Applications,” in *6th IEEE International Conference on e-Learning in Industrial Electronics*, IEEE, 2012.

[23] M. J. C. S. Reis, S. Soares, S. Cardeal, R. Morais, E. Peres, and P. J. S. G. Ferreira, “FouSE: An android tool to help in the teaching of fourier series expansions in undergraduate education,” in *CSEDU 2013 - Proceedings of the 5th International Conference on Computer Supported Education*, 2013, pp. 166–171. doi: 10.5220/0004401101660171.

[24] B. Erişti, Ö. Yıldırım, H. Erişti, and Y. Demir, “An FPGA-based System for Real-time Monitoring of Voltage Harmonics,” in *19th IMEKO TC 4 Symposium and 17th IWADC Workshop Advances in Instrumentation and Sensors Interoperability*, 2013, pp. 677–682.

[25] Z. Khan, M. K. Karim, and M. M. Ashraf, “Design Of A Prototype Model For Harmonics Estimation Of Real-Time Current/Voltage Waveforms By Using MATLAB App Designer At Laboratory Level,” in *MDSRC 2021*, 2021, pp. 1–9.