Jurnal Teknik Elektro dan Komputasi (ELKOM)
Volume 8 Nomor 1 Maret 2026 ‖ Hal. 58-67
ISSN : 2685-1814 (*Print*)
ISSN : 2685-7677 (*Online*)

Experimental Study of Butterworth Active Low-Pass Filters on Light Intensity Variations in Active Voltage Divider Circuits Using Fourier Transform

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Naskah Masuk: 12 Oktober 2025; Diterima: 23 Februari 2026; Terbit: 31 Maret 2026

ABSTRAK

***Abstrak** - Penelitian ini menganalisis kinerja Butterworth active low-pass filter serta rangkaian pembagi tegangan menggunakan pendekatan Transformasi Laplace dan Transformasi Fourier yang divalidasi melalui simulasi MATLAB/Simulink. Butterworth active low-pass filter berbasis rangkaian RC dengan penguat operasional dan masukan DC 110 V menunjukkan bahwa impedansi kapasitor yang dominan pada frekuensi rendah menjaga tegangan antara tetap mendekati nilai input. Konfigurasi op-amp menghasilkan penguatan sekitar 2,5 kali, sedangkan respons frekuensi memperlihatkan penguatan maksimum pada frekuensi rendah dan peredaman pada frekuensi tinggi dengan frekuensi cutoff berada pada kisaran kHz. Transformasi Fourier digunakan untuk mengevaluasi sinyal sinusoidal pada rangkaian pembagi tegangan dengan komponen induktif. Sinyal keluaran memiliki bentuk gelombang dan frekuensi yang sama dengan sinyal masukan, tetapi amplitudonya menurun menjadi sekitar 0,258 kali amplitudo input sesuai rasio resistansi. Analisis domain frekuensi menunjukkan konsentrasi energi pada frekuensi fundamental, dan invers Fourier berhasil merekonstruksi sinyal asal. Simulasi MATLAB menunjukkan kesesuaian tinggi dengan perhitungan teoritis.*

Kata kunci: *Laplace, Fourier, Invers, Sinyal*

ABSTRACT

Abstract **-** This study analyzes the performance of a Butterworth active low-pass filter and a voltage divider circuit using Laplace Transform and Fourier Transform approaches validated through MATLAB/Simulink simulations. An RC-circuit-based Butterworth active low-pass filter with an operational amplifier and a 110 V DC input shows that the dominant capacitor impedance at low frequencies keeps the intermediate voltage close to the input value. The op-amp configuration produces a gain of approximately 2.5 times, while the frequency response displays maximum gain at low frequencies and damping at high frequencies with a cutoff frequency in the kHz range. Fourier Transform is used to emit a sinusoidal signal in a voltage divider circuit with inductive components. The output signal has the same waveform and frequency as the input signal, but its amplitude is reduced to approximately 0.258 times the input amplitude according to the resistance ratio. Frequency domain analysis shows energy concentration at the fundamental frequency, and the inverse Fourier successfully reconstructs the original signal. MATLAB simulations show high agreement with theoretical calculations.

Keywords: Laplace, Fourier, Invers, Signal.

1. INTRODUCTION

The development of analog and digital electronics technology is rapidly advancing in line with the increasing need for systems capable of processing signals accurately and efficiently [1]. One important component in signal processing is the active filter, which functions to pass certain frequencies while attenuating others [2]. Among the various types of active filters, the Butterworth filter is a type of active filter that has a very flat frequency response characteristic in the passband region without any ripple, enabling it to produce stable and smooth output against changes in the input signal frequency [3]. This flat magnitude characteristic makes it often referred to as a maximally flat magnitude filter. This filter was first introduced by Stephen Butterworth in 1930 through his scientific paper entitled “On the Theory of Filter

Amplifiers", which explained the basic principles of designing amplifiers and filters with ideal frequency response. Due to its stability and smooth response, the Butterworth filter is widely used in various applications, such as audio signal processing systems, communications, and measurement instrumentation [4].

In light-based sensory systems such as Light Dependent Resistors (LDRs), the output signal in the form of analog voltage will change according to light intensity. The higher the light intensity, the lower the resistance of the LDR, so that the output voltage from the active voltage divider circuit also varies [5]. However, the signal often contains noise or fluctuations due to environmental changes, so it is necessary to apply an active filter, specifically a low-pass Butterworth filter, to stabilize the output voltage by only passing the low-frequency components that represent the actual changes in light [6].

Analysis of active filter characteristics is performed using two main approaches, namely Laplace Transform and Fourier Transform. Laplace Transform is used to analyze system response in the time domain and complex frequency domain (s-domain), as well as to determine the transfer function, stability, and transient characteristics of the circuit [7]. Meanwhile, the Fourier Transform is used to examine the frequency response of the output signal, in order to determine how the filter affects the frequency components when the light intensity changes. The combination of the two provides a comprehensive picture of the system's behavior, both theoretically and experimentally [8].

This study aims to conduct an experimental study of an active low-pass Butterworth filter integrated with an active voltage divider circuit based on an LDR sensor, as well as to analyze the system response to variations in light intensity using the Laplace and Fourier approaches. Laplace analysis is used to verify the theoretical transfer function, while Fourier analysis is used to evaluate the frequency response of the experimental results.

The novelty of this research lies in the application of two mathematical analysis approaches, Laplace and Fourier, in a single experimental system that combines an LDR sensor and an active Butterworth filter. This approach not only tests the theory through transfer functions but also proves it empirically through spectral analysis of the signal. The results of this research are expected to serve as a reference in the development of light sensor-based instrumentation and automation systems that require stable and adaptive analog signal processing.

2. LITERATURE REVIEW

2.1. Laplace Transform

The Laplace transform is a type of integral transform used to convert ordinary differential equations into linear algebraic equations, or to convert partial differential equations into forms that do not depend on time [9]. In general, this transform is defined for a function $F(t)$ with $t \geq 0$ as follows:

$$\mathcal{L}\{F(t)\} = f(s) = \int_0^\infty e^{-st} F(t) dt \tag{1}$$

s is a real parameter that ensures the existence of the integral.

Through the Laplace transform, the time component in differential equations can be eliminated, making analytical and numerical solutions simpler. This method is often used to analyze dynamic systems, particularly in engineering and physics, and can be solved using numerical approaches such as the finite element or boundary element methods. If the analysis results are needed back in the time domain, the solution obtained must be returned through the inverse Laplace transform [10].

2.2. Low-Pass Filter

This filter is highly useful in various applications, such as audio systems, digital signal processing, and communication systems. In audio systems, a low-pass filter is used to remove unwanted high frequencies that can disrupt sound quality. In digital signal processing, a low-pass filter helps smooth out distorted or noisy signals by reducing rapid fluctuations. In communication systems, a low-pass filter is used to limit the signal bandwidth for efficient transmission and to avoid channel interference, which is crucial in radio and telecommunications

A Low Pass Filter (LPF) is a filter that only allows signals with frequencies lower than the cut-off frequency (fc) to pass through and attenuates signals with frequencies higher than the cut-off frequency (fc). In an ideal LPF, signals with frequencies above the cut-off frequency (fc) will not pass at all (output voltage = 0 V). The RC low pass filter circuit is a type of passive filter, with its frequency response determined by the configuration of R and C used. The basic LPF circuit and the LPF frequency response graph demonstrate how signals are passed or attenuated based on their frequencies. A low-pass filter (LPF) is a circuit designed to allow low frequencies to pass while rejecting or reducing high frequencies. The use of low-pass filters is extensive in various applications, including audio systems, digital signal processing, and telecommunications. This filter functions to reduce unwanted high-frequency interference or to filter noise from the desired signal [11].

2.3. Butterworth Filter

The Butterworth Low Pass Filter is a type of filter known for having a very flat frequency response in the passband region, meaning there is no ripple from 0 Hz to the cut-off frequency. At the cut-off point, the signal amplitude is attenuated by -3 dB. This characteristic makes the Butterworth filter ideal for applications where maintaining signal purity within the desired frequency range is important [12].

An active Butterworth Low Pass Filter uses an op-amp to provide additional amplification and more precise control over the filter's characteristics. In this configuration, the op-amp functions as a voltage amplifier that can increase the amplitude of the signal passing through the filter, according to the application's needs. In a non-inverting configuration, the voltage gain of the active filter is determined by the ratio between the feedback resistor (R2) and the input resistor (R1). The use of an op-amp also allows for high input impedance and low output impedance, which helps prevent excessive loading on the filter and maintains the stability of the cut-off frequency despite changes in load impedance [12].

2.4. Fourier Transform

The Fourier Transform is a very powerful mathematical tool for analyzing signals in the frequency domain. Typically, we describe a function in the time domain, where the (x) axis represents time and the (y) axis represents the signal amplitude value at a particular time. This representation provides a picture of how the signal changes over time. However, in many applications, the time-domain representation does not always provide a complete or most informative picture of the fundamental properties of the signal. Much important information is hidden in the frequency values of the signal [13].

Using the Fourier Transform, we can convert the time-amplitude representation into a frequency-amplitude representation. In the frequency-amplitude representation, the (x) axis represents frequency, and the (y) axis represents the amplitude of specific frequency components. This transformation allows us to see how much of each frequency is present in the original signal. This process can be illustrated by thinking of the signal as a mixture of various sinusoidal waves with specific frequencies and amplitudes, where the Fourier Transform breaks down this signal into its basic sinusoidal wave components [12].

The Fourier Transform is reversible, meaning a function can be transformed into the frequency domain (containing frequency- amplitude information) and then inverted back into the time domain (containing time-amplitude information). However, both sets of information cannot be obtained simultaneously. The frequency domain representation of a function does not contain time information, and vice versa. The Fourier Transform is derived from the complex Fourier integral [12]. The form of the Fourier Transform is as follows

$$f(w) = \frac{1}{2\pi}\int_{-\infty}^{\infty} f(w)e^{iwx}d \tag{2}$$

2.5. Voltage Divider Circuit

A voltage divider circuit is a simple circuit that can reduce high voltage to a lower level. By using just two resistors arranged in series and a single input voltage, we can produce an output voltage that is a fraction of the input voltage. This circuit is often used to create reference voltages from a larger voltage source, provide reference points for sensors, bias amplifier circuits, or bias active components [14].

Basically, a voltage divider circuit can be made with two resistors. The output voltage (VO) from the source voltage (VI) is derived using the voltage divider resistors R1 and R2. The voltage divider circuit is also known as a potential divider circuit. The input is the voltage Vin, which drives the current I to flow through both resistors. Since the resistors are connected in series, the same current flows through each resistor. The effective resistance of the two series resistors is R1 + R2, and the voltage drop across the combination of these resistors is Vin [14].

2.6. LDR (Light Dependent Resistor)

An LDR (Light Dependent Resistor) is a type of resistor whose resistance value changes according to the intensity of light it receives. When exposed to bright light, the resistance of the LDR becomes low, usually ranging from Ω to kΩ. Conversely, in dark conditions, its resistance increases drastically, reaching tens to hundreds of kΩ, even up to MΩ [15].

LDRs are commonly used as light sensors in various applications. One common application is in automatic lighting systems, where the LDR detects the ambient light level to automatically turn the lights on or off. For example, during the day when the LDR detects bright light, its resistance decreases, causing the electronic circuit to turn off the light. Conversely, at night or in dark conditions, the resistance of the LDR increases, causing the electronic circuit to turn on the light [15].

3. METHODE

The Laplace Transformation method and the Fourier Transformation method to analyze the performance of a Butterworth active low-pass filter and an active voltage divider circuit using an LDR sensor. The Laplace Transform is utilized to derive equations in the frequency domain for analyzing and designing the filter's response. In this configuration, a sinusoidal signal is processed through an RC circuit to attenuate high-frequency components, followed by an operational amplifier (op-amp) that amplifies the filtered signal without altering its fundamental frequency characteristics. The use of an op-amp in an active low-pass configuration provides benefits in signal amplification, system stability, and easy adjustment of the cutoff frequency, ensuring a smooth frequency response without ripples in the passband and a sharp attenuation beyond the cutoff point.

Meanwhile, the Fourier Transformation method is employed to examine signals generated by the active voltage divider circuit with an LDR sensor under varying light intensities. This transformation converts time-domain signals into frequency-domain representations, allowing observation of dominant frequency components and their relationship to light variations. In the circuit, the LDR acts as a light-sensitive resistor converting light intensity into voltage signals, the potentiometer controls sensitivity, and the op-amp, inductor, and resistor shape the desired frequency response. The resulting output is observed through a green LED that indicates signal changes. Fourier analysis provides deeper insight into the spectral composition of the signal, facilitating optimization of circuit design and enhancing overall system performance in response to changes in light intensity.

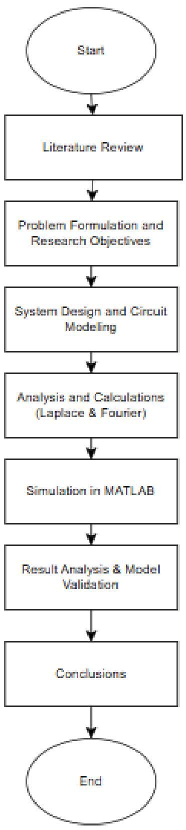

Figure 1. Flowchart

ISSN : 2685-1814 (*Print*)
ISSN : 2685-7677 (*Online*)

4. RESULT AND DISCUSSION

4.1. Laplace Transform

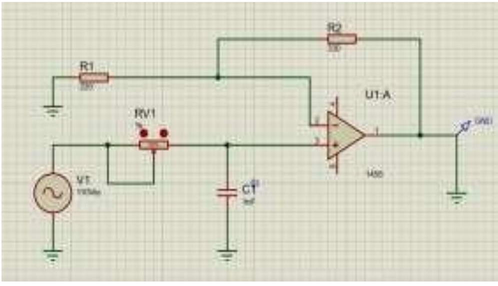

Figure 2. Circuit low pass filter active butterworth

Is known:

$$Vin = 110\,Vdc$$
$$R_1 = 220\,\Omega$$
$$C = 1\,nF = 1 \times 10^{-9}\,F$$
$$R_2 = 330\,\Omega$$
$$RV\ potentiometer\ (50\%) = 1k\Omega \rightarrow 500\,\Omega$$

Calculate the Angular Frequency

$$Xc = \frac{1}{2\pi f C} = \frac{1}{2\pi \times 50 \times 1 \times 10^{-9}} = 3.18 \times 10^{6}\Omega \quad (3)$$

$$VA = \frac{-jXc}{R - jXc} Vm$$
$$= \frac{-j\left(\frac{1}{2\pi fc}\right)}{R - j\left(\frac{1}{2\pi fc}\right)} Vin = \frac{Vin}{1 - \frac{2\pi fRc}{j}} = \frac{110}{1 + j2\pi \times 50 \times 220 \times 1 \times 10^{-9}} \quad (4)$$
$$|VA| \approx 110\,V$$

$$Vo = \left(1 + \frac{Rf}{R_1}\right) \times VA = \left(1 + \frac{330}{220}\right) \times 110 = 275\,V \quad (5)$$

$$Af = \left(1 + \frac{Rf}{R_1}\right) = 2.5 \quad (6)$$

$$fh = \frac{1}{2\pi RC} = \frac{1}{2 \times 3.14 \times 220 \times 1 \times 10^{-9}} \approx 7238\,Hz \quad (7)$$

$$\frac{Vo}{Vin} = \frac{Af}{1 + j\left(\frac{f}{fh}\right)} = \frac{2.5}{1 + j\left(\frac{50}{7238}\right)} \approx 2.500012 - j \cdot 0{,}017276 \quad (8)$$

Laplace Transformation

$$Zc(s) = \frac{1}{sC} = \frac{1}{5 \times 10^{-9}} = \frac{10^9}{5} \quad (9)$$

$$V(s) = Vin(s) \times \left(\frac{Zc(s)}{R_1 + Zc(s)}\right) = Vin(s) \times \frac{\left(\frac{10^9}{5}\right)}{220 + \frac{10^9}{5}} \quad (10)$$

$$Vout(s) = -\left(\frac{R_2}{R_1}\right) Vin(s) = -\left(\frac{330}{220}\right) Vin(s) \left(\frac{10^9}{220s + 10^9}\right) = -1.5 \times \frac{Vin(s)}{1 + 2.2 \times 10^{-7}s} \quad (11)$$

DOI : 10.32528/elkom.v8i1.4320

ISSN : 2685-1814 (*Print*)
ISSN : 2685-7677 (*Online*)

$$H(s) = \frac{Vout(s)}{Vin(s)} = -1.5\left(\frac{1}{1 + 2.2 \times 10^{-7}s}\right) \quad (12)$$

Low Freq
$H(0) = -1.5$
High Freq
$H(S) = -1.5\left(\frac{1}{1 + 2.2 \times 10^{-7}s}\right)$
Invers Laplace
$h(t) = -1.5 \times e^{-2.2\times10^{-7}t}$

Figure 3. Simulation Transfer Funcion Laplace With Simulink In Matlab

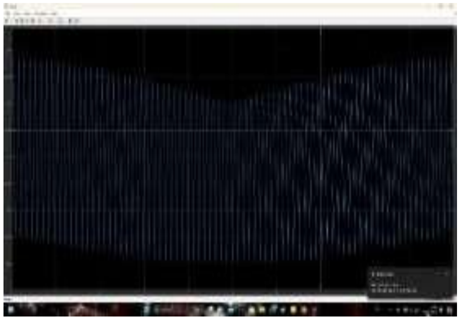

Figure 4. Simulation Output Transfer Funcion Laplace With Simulink In Matlab

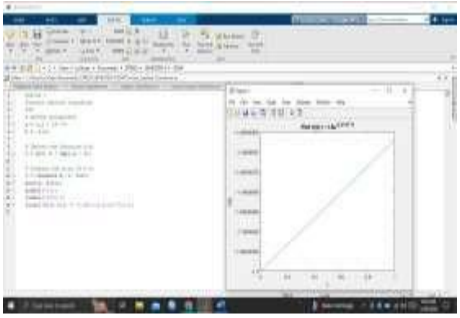

Figure 5. Simulation Invers Transfer Funcion Laplace In Matlab

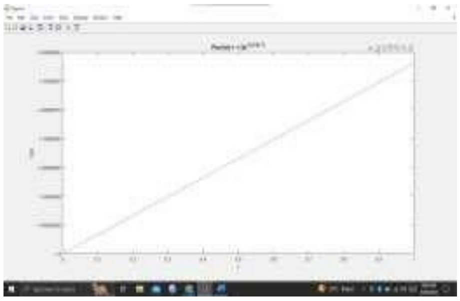

Figure 6. Simulation Output Invers Transfer Funcion Laplace In Matlab

In this analysis, we compare the results of MATLAB/Simulink simulations with manual calculations using the Laplace transform for RC circuit systems with op-amps. The circuit consists of components such as resistors, capacitors, and potentiometers, and accepts an input voltage of 110 V at a frequency of 50 Hz. From the manual calculations, we determine the very large impedance of the capacitor compared to the circuit resistance, as well as the voltage at a certain point in the circuit that is close to the input voltage value. The output voltage of the op-amp is then calculated using a gain factor, resulting in a value significantly higher than the initial input voltage. The transfer function of this system shows that at low frequencies, the output voltage approaches its maximum value, while at high frequencies, the output voltage decreases.

In the MATLAB simulation, the output voltage is modeled as a function of frequency using the same parameters as in the manual calculation. The simulation plot results show the relationship between voltage and frequency on a logarithmic scale, and at a frequency of 1 kHz, the simulation results are very close to the manually calculated values. The agreement of these results proves the accuracy and consistency of both approaches in modeling the frequency response of RC circuit systems with op-amps, indicating that MATLAB simulation and manual analysis can be used effectively to predict the performance of these systems.

Furthermore, in this analysis, we compare the MATLAB simulation results with the theoretical results of the inverse Laplace transform to verify the consistency of the output results. In the MATLAB simulation, an exponential function with negative coefficients is defined, which is plotted on the time interval from 0 to 1 second. The plot results show an exponential function that corresponds to a predetermined formula.

ISSN : 2685-1814 (*Print*)
ISSN : 2685-7677 (*Online*)

Meanwhile, in theoretical calculations using the inverse Laplace transformation, the function in the Laplace domain is converted back to the time domain. This transformation produces the same time function as that defined in the MATLAB simulation. Both methods, both MATLAB simulation and theoretical calculations, provide identical time function results. This shows that the MATLAB simulation results are consistent with theoretical calculations, confirming that the inverse Laplace transform of the given function produces the appropriate output.

Thus, both the manual calculations using the Laplace transform and the MATLAB simulations show consistent and accurate results in analyzing RC circuit systems with op-amps, both in the frequency domain and the time domain. This confirms that both methods can be used to predict and verify the performance of electronic circuit systems effectively.

4.2. Fourier Transform

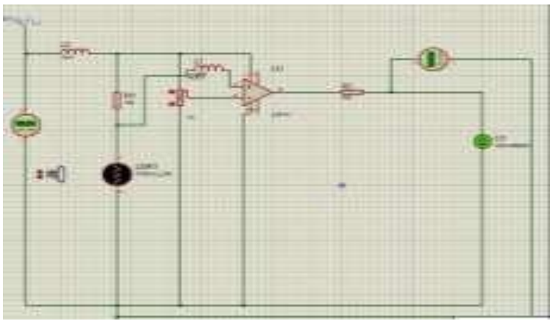

Figure 7. Volatge divider circuit

Is known:

$$Vin = 12\,V$$
$$f = 1\,kHz$$
$$L = 1\,mH = 1 \times 10^{-3} H$$
$$R_1 = 10\,k\Omega$$
$$R_2 = R_3 = R_4 = R_5 = 220\,\Omega$$

Impedance

$$ZL = \omega L = 2\pi f L = 2 \times 3.14 \times 1000 \times 1 \times 10^{-3} = 6.28\,\Omega \quad (13)$$

$$Z = \sqrt{R^2 + XL^2} = \sqrt{10000^2 + 6.28^2} = 10000.197\,\Omega \quad (14)$$

$$Imax = \frac{V}{Z} = \frac{12}{6.28} = 1.91\,A \quad (15)$$

$$VL = I \times XL = 6.3 \times 6.28 = 39.56\,V \quad (16)$$

$$f_s = \frac{f_r}{2} = \frac{15.72}{2} = 7.86\,Hz \quad (17)$$

$$I = \frac{V}{R} = \frac{12V}{10k\Omega} = 0.12\,mA \quad (18)$$

Fourier Series:

$$f = 1\,kHz \rightarrow T = \frac{1}{f} = 1\,ms \quad (19)$$

$$Vin(t) = 12\sin(\omega t) \quad (20)$$

ISSN : 2685-1814 (*Print*)
ISSN : 2685-7677 (*Online*)

$$Vout(t) = Vin(t) \times \left(\frac{R_2}{R_1 + R_2}\right) = 12\sin(\omega t) \times \left(\frac{220}{10220}\right) \approx 0.258\sin(\omega t) \quad (21)$$

Fourier Transform:

$$\begin{aligned} F\{\sin(2\pi f t)\} &= \frac{1}{2i}[\delta(f - f^0) - \delta(f + f^0)] \\ \hat{V}(f) &= \frac{0.258}{2i}[\delta(f - 1000) - \delta(f + 1000)] \end{aligned} \quad (22)$$

$$Inverse\ Fourier \rightarrow f(t) = 0.258\sin(2\pi(1000)t) \quad (23)$$

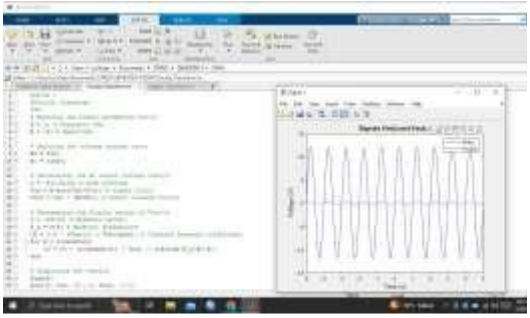

Figure 8. Simulation Transfer Funcion Fourier In Matlab

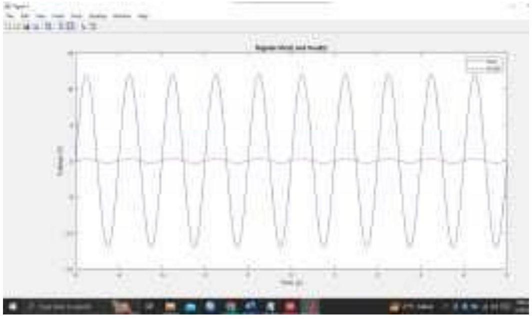

Figure 9. Simulation Output Transfer Funcion Fourier In Matlab

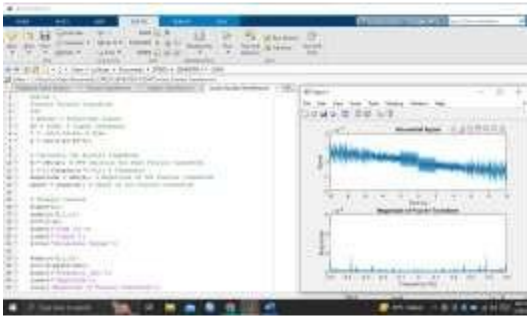

Figure 10. Simulation Invers Transfer Funcion Fourier In Matlab

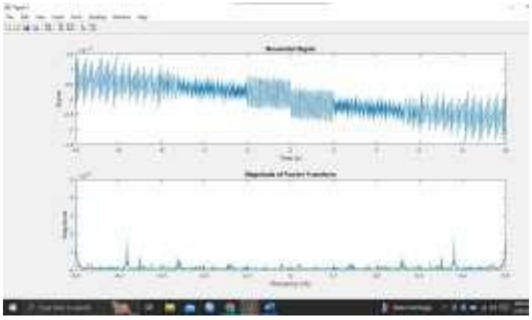

Figure 11. Simulation Output Invers Transfer Funcion Fourier In Matlab

In this analysis, we compare the results of MATLAB simulations with theoretical calculations to verify if the output results are consistent. The input signal used has an amplitude of 12 V in both approaches, but there is a difference in frequency. The MATLAB simulation uses a frequency of 1 Hz, while the theoretical calculation uses a frequency of 1000 Hz. Both methods use a voltage divider with resistance values R1 of 10220 Ω and R2 of 220 Ω to produce the output signal. The results of both methods show that the output voltage is a sinusoidal signal with a lower amplitude, approximately 0.258 of the input signal amplitude. The output signal retains a similar shape to the input signal but with a reduced amplitude according to the voltage divider ratio.

The Fourier series calculation in the MATLAB simulation is performed to obtain the harmonic coefficients of the output signal, but there is inaccuracy because the frequency used is different from the theoretical calculation. The theoretical calculation provides more accurate Fourier series results with a clear input signal. The main conclusion of this analysis is that the frequency used in the MATLAB simulation must be adjusted to 1000 Hz to be consistent with the theoretical calculations. With this adjustment, the output results from the simulation and theoretical calculations will align, showing that the output signal has an amplitude consistent with the voltage divider ratio and retains a sinusoidal shape consistent with the input signal.

Furthermore, in this analysis, we compare the MATLAB simulation results with the theoretical results of the inverse Fourier transform to verify the consistency of the output. In the MATLAB simulation, a sinusoidal signal with a specific frequency is defined and then analyzed using the Fast

Fourier Transform (FFT). The FFT results provide the magnitude and phase of the signal in the frequency domain. Subsequently, the Inverse Fast Fourier Transform (IFFT) is used to convert the signal back to the time domain, and the results are plotted to show consistency with the original signal.

Meanwhile, in theoretical calculations using the inverse Fourier transform, the function in the frequency domain is converted back to the time domain. This process demonstrates that the original sinusoidal signal can be accurately reconstructed from its frequency representation. Both methods, the MATLAB simulation and the theoretical calculations, show consistent results, namely a sinusoidal signal with the same frequency and shape. This indicates that the MATLAB simulation results align with the theoretical calculations, confirming that the Fourier transform and its inverse produce accurate and consistent output.

Thus, both the theoretical calculations and the MATLAB simulations show that the Fourier transform and inverse Fourier transform can be used to predict and verify the performance of signal systems effectively. When used with appropriate parameters, both methods provide consistent and accurate results in analyzing sinusoidal signals, in both the time domain and the frequency domain.

5. CONCLUSION

In this analysis, MATLAB/Simulink simulations were compared with manual calculations using the Laplace transform for RC circuits with op-amps, confirming that both methods effectively predict frequency response and performance. The manual calculations determined that the capacitor's impedance is significantly larger than the circuit resistance, and the output voltage, calculated using a gain factor, was substantially higher than the input voltage. For a voltage divider circuit with resistance values R1 of 10220 Ω and R2 of 220 Ω, adjusting the simulation frequency to match the theoretical calculation frequency of 1000 Hz was necessary. Both approaches then showed consistent sinusoidal output signals with an amplitude approximately 0.258 of the input signal amplitude, demonstrating the importance of matching simulation parameters with theoretical conditions.

Additionally, MATLAB simulations and theoretical calculations using inverse Laplace and Fourier transforms showed consistent results. Both the MATLAB simulation and theoretical approach for the inverse Laplace transform produced identical time-domain functions. For the Fourier transform analysis, the MATLAB Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) accurately replicated the sinusoidal signal's frequency and shape. These findings verify the accuracy and reliability of MATLAB simulations in modeling these systems, highlighting their effectiveness in predicting and verifying the performance of RC circuits with op-amps and voltage divider circuits. This comprehensive validation underscores MATLAB's robustness as a simulation platform for complex electrical and electronic systems.

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